# TREE VOLUME MODELS FOR TROPICAL BROADLEAVED FORESTS

## With particular reference to the forests of the Northern Territory

by

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## ORIGINALITY OF THESIS

Except where otherwise acknowledged, the work described in this thesis is my own original work.

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# ABSTRACT

Tree volume data for tropical hardwood species were collected from a number of localities in the Northern Territory by forestry field staff between 1967 and 1972. The major species represented in the data were *Eucalyptus miniata*, *E. tetrodonta*, *E. nesophila*, *E. bleeseri* and *Melaleuca* spp. (botanical nomenclature after Chippendale, 1971).

The basic data consisted of quartile diameter measurements along the merchantable bole of each tree. These data were processed to obtain estimates of gross merchantable volume under bark.

The data were grouped by species of major occurrence within each forest area. Grosenbaugh's (1967) linear regression program was used for fitting and testing linear volume models. The model

$$V = b_0 + b_1 D^2 H + b_2 D^3$$

- weighted by $1/(D^2 H)^2$ to correct heterogeneous variance - was found to fit satisfactorily, and was used for covariance analysis to test for differences between localities within each species. It was found that in most cases data for the same species from adjacent forest areas could not validly be combined. Additional work indicated that differences between forest types within species may also be significant.

The final groupings were used to develop final volume models. Bard's (1967) non-linear regression program

was used for testing non-linear models. A model of the form

$$V = b_0 + b_1 D^{b_2} H^{b_3}$$

was found to be superior to several linear models and was fitted to all of the final data groupings.

# PART I : BACKGROUND

## CHAPTER 1 : INTRODUCTION

Forest inventory provides the basis for most forest management decisions. Although techniques are well developed for temperate forest conditions - and in particular for plantation conifers - relatively little work has been done on the problems of estimating stand volumes in tropical forests. With projected increases in world demand for wood and wood products and the rapid depletion of traditional sources in temperate countries, the relatively underdeveloped forests of the tropics are fast assuming a greater importance than ever before (FAO, 1974; Keays, 1975). It is against this background that some aspects of stand volume estimation will be considered in this study, with particular reference to the application of tree volume tables to the tropical forests of the Northern Territory.

### (i) THE NEED FOR PRECISE AND UNBIASED ESTIMATES OF STAND VOLUME

In recent years the traditional objectives of forest inventory have changed. Carron (1974) has reviewed the way in which changes in management objectives have led to the use of recent developments in biometric techniques, computing facilities and remote sensing to obtain answers to more wide-ranging questions on growth, yield and stand dynamics. Workers have turned to the problems of multi-resource inventories and land use planning (e.g., Madgwick, 1967).

Against such a background it is easy to lose sight of the importance of basic estimates of the volume of utilisable wood in a forest. However, the need for such information is greater than ever before if forest managers are to make sound decisions in the face of a number of alternative land use possibilities.

Quantitative information on the forest resources of tropical areas is particularly lacking. It is from these areas that most of the world's future needs must be satisfied. In view of the costs involved in setting up a modern pulpwood operation, it is not unreasonable for potential investors to expect precise and unbiased estimates of wood volumes.

Mixed hardwood forests in the Northern Territory constitute a resource which, while not necessarily prominent by world standards in terms of volume per unit area, may well become more important in the future as forests in neighbouring countries in South East Asia are depleted. In addition, the inevitable increase in the population of northern Australia will lead to competing land pressures and the need for adequate land use planning. For this purpose as well, precise and unbiased estimates of stand volumes are essential.

## (II) METHODS OF STAND VOLUME ESTIMATION

Before methods of stand volume estimation are discussed, it is essential to clarify the type of volume to be estimated. The volume of interest to a forest manager may range from "the entire tree from the root hairs to the leaves" (Young, 1968) to the other extreme of only the best and straightest merchantable logs from a rare species within the stand.

In natural stands of hardwoods, the volume of interest is usually the bole volume from stump to some limiting factor at the small end of the bole such as crown break, a minimum small end diameter or some form of defect. This is the volume to be considered in this study.

A volume estimate for a stand can be obtained either by a complete enumeration of all individual trees (usually impractical, although reported by Brunig (1963) for tropical peatswamp forests in Sarawak), by taking a sample of trees, or by some approach involving the measurement of stand variables. When a sample of trees is taken, their volumes may be determined either by direct measurement or by the use of tree volume tables. Measurement of stand volume usually involves the use of stand volume tables. These and other methods are discussed below.

### (a) Sample Tree Methods

One of the oldest methods of stand volume estimation - described by Spurr (1952) and Carron (1968) - is to isolate the tree of mean volume within a stand, measure its volume and then multiply by the number of trees in the stand. Whether the choice is merely the tree of mean basal area or is based on a more complex selection scheme, both Spurr and Carron state that the method generally requires an excessive amount of work to achieve a satisfactory result. The sample tree method in this form is also most suited to forest stands which are far more homogeneous in volume than the mixed broadleaved forests of the tropics.

However, methods involving direct volume estimation of individual trees have been developed in recent years, together with sampling schemes more sophisticated than those used with earlier sample tree methods. Direct volume estimation by height accumulation was first proposed by Grosenbaugh (1954) as a simple formula for tree volume based on upper stem diameters read in diminishing arithmetic progression up the tree. Enghardt and Derr (1963) found the method to be efficient for young evenaged stands of southern pine, with a Spiegelrelaskop providing sufficient accuracy for the diameter and height readings. Barrett (1964) found the method accurate in tests on felled trees and Lohrey and Dell (1969) developed computer programs to compute sample tree volumes by height accumulation. Arney and Paine (1972) used the method with a telescopic Spiegelrelaskop and obtained results comparable in accuracy to previous measurements with a Barr and Stroud dendrometer.

Whether selected trees are to be measured by height accumulation or some other method, a number of sophisticated sampling schemes exist for the selection of sample trees.

A special case of using probability proportional to size has been developed by Grosenbaugh (1963, 1964, 1965, 1967). Called 3-P sampling (probability proportional to prediction), it is applied in the special case where all units of a population are visited during sampling and involves selection of sample trees with a probability proportional to some estimate of their size, such as estimated height or estimated volume.

Schreuder _et_ _al_. (1971) compared the method with some other sampling methods and, by simulating each method on three forest populations, found 3-P sampling to give somewhat less precise results than another method (systematic sampling with probability proportional to size for cumulated measures of size). Seppälä (1971) found 3-P sampling and optimum stratified sampling nearly identical in efficiency during a comparison using six stand sample plots in Finland, and commented on the disadvantage of variation between actual and planned sample size. Steber and Space (1972) reported the successful application of 3-P sampling - together with the computer program developed by Grosenbaugh (1971) for associated dendrometer measurements - to the inventory of a large forest in northern Florida and southern Georgia, with a considerable saving of time over conventional techniques. Van Hooser (1972) reported similar results from a simulated

3-P sample in southern Alabama, and Bonnor (1972) found 3-P sampling much more efficient than point or plot sampling in a study in western Canada.

Direct volume measurement on felled trees was used by Johnson and Hartman (1972) for estimating stand volumes in western Oregon, with 3-P sampling used for sample tree selection. The results from direct measurement were compared with both dendrometer and volume table estimates on standing trees. Aggregate errors of from 0.6 to 10.7% were found in the standing tree estimates.

Sample tree methods are more applicable to evenaged stands than to heterogeneous tropical forests. Specialised methods involving the use of dendrometers or other expensive equipment are as yet unproven for tropical forests, where the problems of accessibility and often harsh field conditions are generally associated with shortages of trained staff. Methods involving direct measurements on felled trees also involve major logistical problems for most tropical forests, making them impractical for extensive sampling.

(b) Methods Using Remote Sensing

The term "remote sensing" covers the use of the ultraviolet, visible, infrared and microwave regions of the electromagnetic spectrum to collect data that give a measure of the reflectance, emittance, surface geometry and temperature of plants, soils and water (Luney and Dill, 1970).

Conventional aerial photography is the form of remote sensing most commonly used for forestry applications.

Husch _et al_. (1972) describe three methods for estimating stand volume directly from aerial photographs: individual tree volume estimation, stand volume estimation from stand measurement, and volumes from ocular comparisons with photographs of stands of known volume.

The first method, otherwise described as the use of aerial tree volume tables, was used by Bonnor (1964) for red pine, using tree height measurements from aerial photographs and diameters estimated from a d.b.h.-crown width relationship. Similar relationships have been developed for hardwoods by Burrows and Strang (1964) and Curtin (1964), while Dawkins (1963) has reviewed similar work on seventeen tropical species. Francis (1966) correlated merchantable volume of tropical rain forest trees in Sabah with crown area measurements from air photos, but excluded tree height measurements because of the difficulty in obtaining them and their inadequate correlation with merchantable bole length. Hitchcock (1974) also used only crown measurements for volume estimates of ponderosa pine in Arizona.

Tree volume estimates from low level large scale photographs have been developed in Canada by Lyons (1966, 1967), Sayn-Wittgenstein and Aldred (1967) and Westby _et al_. (1968), using both height and crown area.

Aerial stand volume tables use variables such as stand height and density. Rogers (1960) obtained preliminary volume estimates for the Caspian forests of Iran using mean tree height, mean crown density and proportion of forested land as determined from photo plot measurements. Although Spurr (1952) claimed that aerial stand volume tables were more commonly used than aerial tree volume tables because of difficulties in distinguishing individual trees on medium scale air photos, the work with large scale photography described above has tipped the balance in the other direction.

Direct ocular comparisons of the photographic image with standard stereograms of areas of known volume is a subjective method, based on the premise that a competent photo-interpreter can see much more in the stereoscopic image than can be expressed by simple measurements of tree height, crown diameter and crown closure (Spurr, 1952). This method was used by Swellengrebel (1965) for a preliminary reconnaissance survey of tropical rain forest in West Irian, but it was found that variation in photography and operator fatigue lead to problems in consistency of interpretation.

Spurr found serious errors in direct volume estimates from air photos, and recommended their use as an adjunct to ground surveys rather than as a primary source of stand volume estimates. He found that estimates obtained from combined air photo-ground cruises were considerably more accurate than direct air photo estimates and were faster than purely ground methods. Boon (1970) also recommended this procedure for inventory of tropical rain forest, claiming that methods of estimating volume directly from air photos which were successful in temperate forests usually failed in tropical rain forest, mainly due to the heterogeneous species composition. MacLean (1972) also favoured joint aerial and ground methods, and demonstrated considerable improvements in sampling efficiency of double sampling on air photos over simple field sampling.

Other forms of remote sensing such as infrared line scanning (Hirsch, 1965), side looking aerial radar (FAO, 1973) and satellite photography (Heath, 1974) are of interest for forest type classification, or as sampling frames for multi-stage sampling (Langley, 1969), but at present they seem to have little potential for direct stand volume estimation.

### (c) Stand Volume Tables

Stand volume tables are used to estimate stand volume per unit area from variables such as stand basal area, stand mean height or top height and stand form factor; short cut methods of measuring stand basal area by point sampling (Grosenbaugh, 1952) are usually used. Spurr (1952) found that stand volume tables gave best results with fully stocked stands of evenaged conifers, but they have been applied to irregular stands in some cases. Malik (1968, 1969) developed and tested a method for forests in Pakistan which was equivalent to a single entry stand volume table based on stand basal area, but his standards of comparison make evaluation of the method difficult. Cromer and Carron (1956) developed two-variable stand volume tables for Pinus radiata in the A.C.T. based on stand basal area and a measure of stand mean height; the tables enabled stand volume to be predicted almost as well as with a four-variable tree volume table, and in less than 1% of the time.

Evert (1969a) developed a three-variable stand volume table by the ingenious use of basal area sweeps both at breast height and a fixed upper height, using a relascope and a height pole, to produce an estimate of stand form quotient. Powell (1969) introduced a third variable by estimating ocularly the Girard form class of each tree in the sample, but, as noted by Spurr (1952), such subjective estimates of form can introduce a degree of bias which offsets any potential gains in precision.

Stand volume tables can be difficult to apply in mixed unevenaged forests. If the forest is extremely irregular or patchy in structure then figures for mean stand height or stand basal area may have limited meaning, and in addition there is the problem of how much of the small size classes to include in the measurements for determining such parameters. If merchantable volumes are required then merchantable bole lengths must be measured in preference to total tree heights, and mean values for log lengths of some merchantable standard may obviously have very little application to stand conditions. But by far the most serious problem with the use of stand volume tables in a mixed forest is the difficulty of partitioning the overall stand volume estimate by species: where species vary both in quality and potential end uses, such estimates are essential.

(d) Tree Volume Tables

The commonest form of stand volume estimation in heterogeneous forests involves the use of tree or stand volume tables. The inventory is confined to relatively simple measurements such as tree diameter and height, or stand basal area and stand height, and a subsample is used to determine the relationship between these parameters and tree or stand volume. Tree volume tables relate tree volume to one or more independent variables, i.e., tree diameter, height and some measure of form, plus in some cases bark thickness.

Single entry tree volume tables usually relate tree volume to diameter at breast height (d.b.h.), and are generally most suited to evenaged stands. However some attempts have been made to apply them to heterogeneous unevenaged hardwood stands. Banks and Burrows (1966) produced single variable tree volume tables for merchantable volume of each of three Rhodesian woodland species, which gave acceptable results because of the fact that bole length was reasonably constant among trees of merchantable size. Wong (1966) developed a single entry table for lowland Dipterocarp forest in Malaya which included large numbers of different tree species, but he predicted "total" volume (bole plus branchwood) rather than merchantable bole volume and also grouped the data into two size classes to produce a satisfactory fit over the whole range. He also recommended the use of existing two-variable volume tables (Vincent and Sandrasegaran, 1965b) for the estimation of merchantable volume rather than total volume, because of large variations in proportions of bole and branchwood between species. Chaturvedi (1973) obtained results similar to those of Wong, finding a good correlation between diameter and the total of timber bole volume and branchwood volume, for teak in India.

Local or single entry tree volume tables were produced for tropical rain forest species in the British Solomon Islands by Bengough (1965, 1966) and Bengough and Burn-Murdoch (1967). However each table covered only a single species in a particular locality and forest type, and a method to "test and re-localize" the tables was recommended if they were to be applied to other areas.

Two-variable tree volume tables, using tree d.b.h. and height to predict volume, are the most common form of volume table. Tree height is either measured directly for each tree or in some cases predicted from a subsample of tree height measurements by relating height to diameter (e.g., Ker and Smith, 1955, 1957; Malik, 1968). More work has probably been done with two-variable tree volume tables as a method of stand volume estimation than any other method, starting with the tables produced by graphical methods in the 1800s through the early development of mathematical models by workers such as Schumacher and Hall (1933) to the routine use of computer fitted volume regressions for modern inventory. This is discussed in further detail in later chapters.

Because trees of the same d.b.h. and height may differ in volume, many attempts have been made to include some measure of tree form as an additional variable. If the volume of a tree is represented by

volume = basal area x height x form factor

then the form factor will be that fraction of the volume of a cylinder of the same basal area and height occupied by the tree. Because such factors are "abstruse concepts" (Spurr, 1952) and difficult to evaluate for standing trees, various indicators of tree form have been used. Chapman and Meyer (1949) describe both form quotient (the ratio of diameter at half height above breast height to d.b.h.) and Girard form class (the ratio of diameter under bark at 16 feet (4.9m) to diameter over bark at breast height). As Carron (1968) has noted, a form quotient based on diameter at half total height can only be applied effectively to trees which have a single stem from ground to tip; their application to deliquescent hardwoods which lack such a continuous stem would therefore be inappropriate. However Hegyi (1965) used an index somewhat analogous to the Girard form class for tropical rain forest trees in British Guiana, based on the difference between diameter at breast height or above buttress and diameter at a fixed distance of 15 feet (4.6m) above this point.

Golding and Hall (1961) obtained marked increases in precision of the volume estimate for three North American conifers by adding form quotient as a third variable in volume tables. However Simpfendorfer (1959) obtained only a small increase in precision with *Pinus radiata* in Victoria when a measure of form was added. As noted by Spurr (1952), all measures of form have been found to vary independently of both diameter and height, and it is necessary to take a measure of form for each tree sampled if the precision of the volume estimate is to be improved. This adds considerably to the time taken for field work and, even after the successful results reported above, Golding and Hall recommended a two-variable tree volume equation as combining a sufficiently high precision with ease of use. And after reviewing the problem, Spurr concluded: "The complexities introduced by the form class technique seemingly outweigh the theoretical improvement in volume estimate."

A fourth variable - bark thickness - was included in a general volume table for plantation *Pinus radiata* by Cromer *et al*. (1955). However their table was designed to give precise estimates of volume for individual plantation-grown trees, and is not appropriate to the estimation of overall stand volumes in mixed tropical hardwood forests.

Tree volume tables are a suitable method for mixed hardwood forests in general, and for tropical forests in particular. The use of three variables - including an estimate of tree form - requires the time-consuming measurement of upper stem diameters on every tree if precision is to be improved, and this is usually difficult to justify in terms of maximum precision achievable for a given inventory cost. The use of only one variable (diameter) involves problems in the applicability of the tables outside very localised areas.

Two-variable tree volume tables are the only alternative. As described in FAO's (1973) "Manual of Forest Inventory", these can be applied either directly by measuring both diameter and height of every tree in the sample, or indirectly by measuring heights of only a subsample and then relating height to diameter. The second method has been used by Ker and Smith (1957) in Canadian forests, by Malik (1968) for naturally occurring conifers in Pakistan, by Sandrasegaran (1970) for plantation conifers in Malaya, by Chaturvedi (1973) for teak in India, and by Carron (1968) for eucalypt forests in Australia. The relative efficiency of either method obviously depends on the time taken for tree height measurements in the forests covered by the inventory.

# CHAPTER 2 : THE TROPICAL FORESTS OF THE NORTHERN TERRITORY

The area of the Northern Territory which is of major forestry interest lies north of the 30" (762mm) isohyet (Figure 2.1). The whole area is of generally low relief, ranging from extensive coastal plains where relief is generally less than 10 metres to dissected plateaux which, while being very rugged and broken, do not include points higher than about 400 metres above sea level. Forest resources of commercial interest are confined to the plains.

The climate is of a tropical monsoon type, with mean daily temperatures in the approximate range 22-32°C over the whole area throughout the year, and a markedly seasonal rainfall with 80-85% of the average annual rainfall from December to March and virtually none from May to September. Mean relative humidity ranges from approximately 50% to 70% during the dry season, and from 70% to 80% during the wet season.

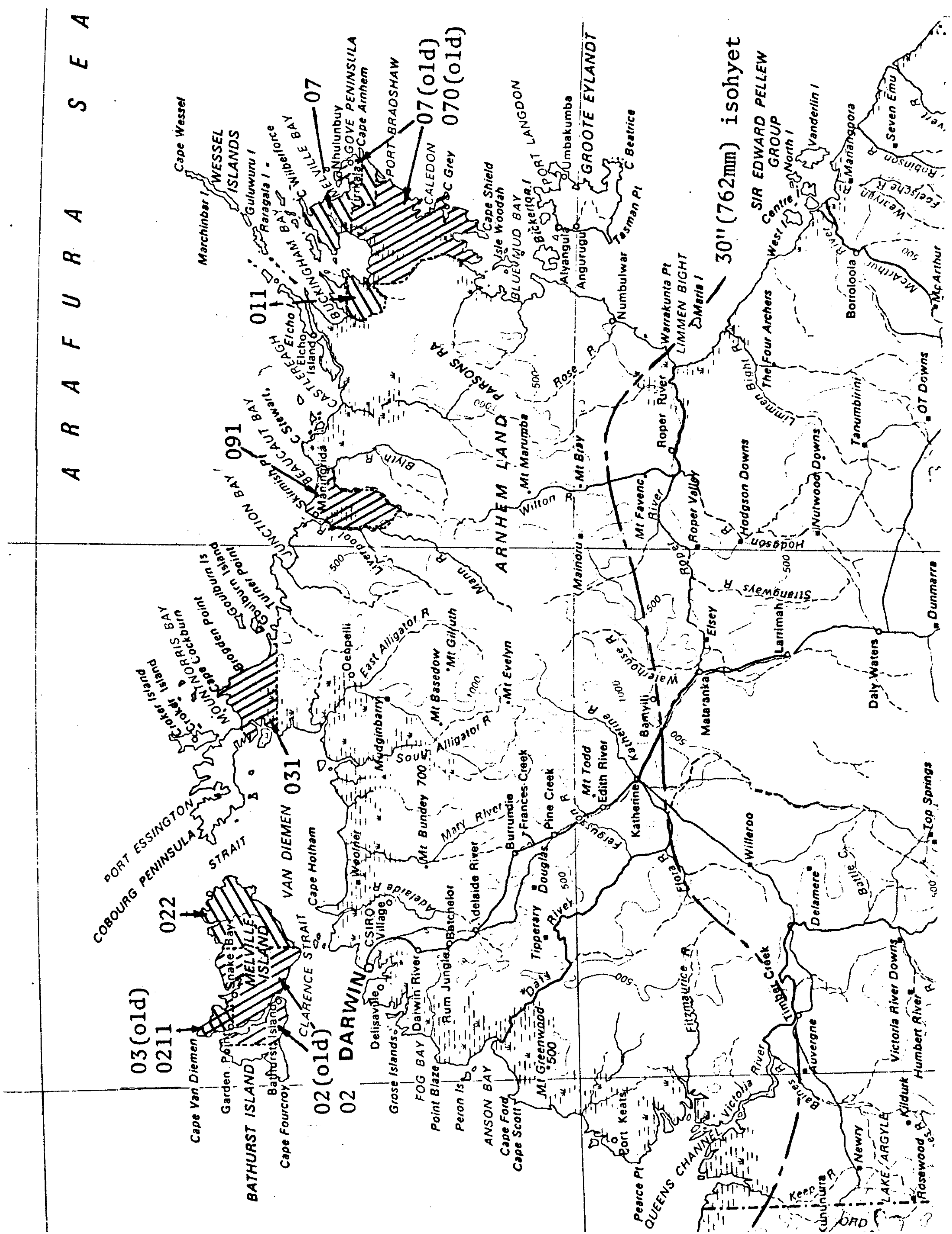
## (i) FOREST TYPES AND TREE SPECIES

Forest types occurring in the Northern Territory are shown in very broad terms on the map of vegetation regions in the Atlas of Australian Resources (Williams, 1955). A classification of greater forestry interest is given by Stocker (1972) as follows:

Figure 2.1

The area of major forestry interest in the Northern Territory. Forest areas of interest to this study are cross hatched and flagged with their locality codes.

Key to locality codes: Appendix 1



a. Mangrove and beach vegetation

b. Monsoon forest

c. Swamp forest

d. Riparian forest

| | |
|---|---|
| e. Tall open forest | ) including |
| | ) cypress |
| f. Low open forest and | ) pine stands |
| savannah woodland | ) |

The most extensive forest type with commercial potential is tall open forest. The dominant tree species are (nomenclature after Chippendale, 1971) Eucalyptus miniata and E. tetrodonta, which are by far the most common species in the whole area. The better forest has dominant trees over 20m in height, with occasional trees over 30m on the best sites. Other associated species include major occurrences of E. nesophila on Melville and Bathurst Islands and Cobourg Peninsula, and other less common species such as E. bleeseri (mainly on low stony ridges) and E. polycarpa (often bordering heavy soils near watercourses). In addition there are a number of understorey species such as Erythrophloeum chlorostachyum (which can occasionally form part of the canopy) and various species of Eugenia and Terminalia, plus a number of other species in the shrub layer. Callitris intratropica (northern cypress pine) occurs in small groups scattered throughout various areas including northern Arnhem Land and areas near Borroloola and Dorisvale; however it has not been included in this study of volume tables for broadleaved trees.

Low open forest and savannah woodland is of limited commercial interest in areas where it is the major forest type, but it also occurs on patches of heavy, poorly drained soils throughout areas of tall open forest. The main tree species include _E_. _dichromophloia_ and _E_. _latifolia_, which generally do not exceed 15m in height.

Large areas of swamp forest occur throughout the coastal plains, on heavy black soil areas which are usually flooded for most of the year. The main species is _Melaleuca cajuputi_, which grows to sizes larger than any other tree species found in the Northern Territory (up to 40m). Other species include _M_. _leucadendron_, _M_. _nervosa_ and _M_. _viridiflora_.

Other vegetation types are of little or no commercial interest, with the exception of the limited use of some species from the small patches of monsoon forest which occur on well watered sites. Descriptions of other forest types are given by Stocker (1972) and a check list of plant species recorded from the Northern Territory has been compiled by Chippendale (1971).

## (ii) HISTORY OF COMMERCIAL EXPLOITATION

The first European settlements in the Northern Territory were short-lived attempts at Fort Dundas on Melville Island (1824-1829), Fort Wellington in Raffles Bay (1827-1829), Victoria at Port Essington (1838-1849) and

Escape Cliffs in Adam Bay (1864-1867). These failures are described by Bauer (1964). Local timber was used for buildings and fuel.

Following permanent settlement at Palmerston (Darwin) in 1869 the population grew to 5000 by 1890. Timber cutting and hauling are referred to by Bauer under the heading of "Miscellaneous Industries" for this period, and mainly involved the cutting of cypress pine in many areas at varying distances from Darwin. Much of the worthwhile accessible forest appears to have been cut out by about 1910, but limited cutting probably continued after that date.

During the second world war the Army cut timber from various localities for military purposes (Bateman, 1955; Stocker, 1972), leaving many of the stands within easy reach of Darwin in a degraded condition. By 1953 there was a number of small mills between Cobourg Peninsula and Katherine, mostly cutting cypress pine from scattered stands at long distances from their mill sites (Bateman, 1955).

In 1959 the Forestry and Timber Bureau established a research station in Darwin, and this was followed by the establishment of a Forestry Branch within the Northern Territory (N.T.) Administration in 1967. A five year forestry programme was begun in 1970 which included the establishment of sawmills at Snake Bay on Melville Island and at Maningrida and Murgenella in northern Arnhem Land.

Sawn timber production in the Northern Territory has not been high in recent years. Bateman (1955) estimated that the total output of all mills in 1953 was approximately 3500 cubic metres per annum, and more recently the output from existing mills for the period from July 1971 to June 1974 totalled approximately 8000 cubic metres. However, although several writers have commented on the shortage of mill logs in Northern Territory forests (Bateman, 1955; Bauer, 1964; Stocker, 1972), the following comment from Stocker is relevant:

> "Despite these limitations the eucalypt forests contain a great bulk of wood which may some day serve as a source of raw material for a wood-fibre industry."

## (iii) HISTORY OF FOREST INVENTORY

### (a) Early Investigations

Bauer (1964) refers to "much searching" for additional cypress pine stands at the turn of the century, following the growing scarcity of timber. Some preliminary investigations of the forest resource were carried out in the early 1930s and during the 1939-45 war by M.R. Jacobs (pers. comm.). The first formal inventory survey recorded was carried out by Shillinglaw (1944) for the Army. He covered an area from the Daly River to Melville Island and east to Cobourg Peninsula, but concentrated most of his efforts on swamp forests of paperbark (Melaleuca spp.) around the lower reaches of the Reynolds, Daly and Finniss Rivers.

Between 1950 and 1953 an officer of the Forestry and Timber Bureau examined the forest resources of the Northern Territory and wrote a report (Bateman, 1955) on the results of the investigation. He confined his attention to sawlog material and assessed a wide range of areas of eucalypts, paperbark and cypress pine as carrying volumes from 0.2 to 1.7 cubic metres per hectare.

Following the establishment of the Forestry and Timber Bureau station in 1959, a number of areas were investigated by Bureau staff. These included an inventory of cypress pine near Borroloola in 1962 and near Dorisvale in 1964, followed by intensive mapping and sampling of cypress pine areas near Murgenella and Maningrida in northern Arnhem Land during 1965 and 1966. A reconnaissance of hardwood areas on the Gove Peninsula was also carried out.

(b) Recent Inventory

The major hardwood inventory surveys began after the setting up of the N.T. Forestry Branch in 1967. Two areas on Melville and Bathurst Islands and one at Gove were covered during 1968 and 1969. Some changes were made to data recording procedures in 1970 and an additional nine areas were inventoried up to 1974. During this period air photo interpretation was also carried out over other areas preparatory to field inventory.

Figure 2.1 shows the forest inventory areas relevant to this study. These are areas covered between 1967 and 1972 where hardwood tree volume table data were also collected.

The inventories were carried out by a process of double sampling. The first phase consisted of a random sample of air photo plots (0.2 hectare, circular) which were interpreted in classes of stand height and crown closure, together with a soil drainage class. This method of stratifying for forest inventory has been described and evaluated by Aldrich (1953), Loetsch and Haller (1964) and others, and is commonly used in forest stands where forest types cannot be easily delineated by conventional mapping techniques (Spurr, 1952). The forest type classes used in the Northern Territory are shown in Table 2.1. These were developed by L.J. Beens, a former officer of the N.T. Forestry Branch, before the publication of Specht's (1970) vegetation classification, and, in view of their similarity to Specht's classes, were considered sufficiently comparable to be left unaltered (L.J. Beens, pers. comm.).

After each forest area had been stratified in this way, a stratified subsample of the photo plots was selected as the second phase for field measurement. Each plot selected was then located as accurately as possible in the field and details of tree species, d.b.h., bole length, merchantability and stand height were recorded, together with assessments of other site factors. Tree volume table data

Table 2.1

Forest type classes used for photo plot stratification of Northern Territory broadleaved forests for forest inventory.

Crown Closure Classes

| code | closure |
|---|---|
| 0 | 0% |
| 1 | 0 - 5% |
| 2 | 5 - 15% |
| 3 | 15 - 35% |
| 4 | 35 - 65% |
| 5 | 65 - 100% |

(plus additional alphabetic codes for cypress pine which are not relevant to this study)

Stand Height Classes
(indicated by column position of crown closure code)

| column position | height class (before 1970) | height class (from 1970) |
|---|---|---|
| 1 | over 25m | over 30m |
| 2 | 10 - 25m | 20 - 30m |
| 3 | under 10m | 10 - 20m |
| 4 | | under 10m |

Soil Drainage Classes

| code | drainage |
|---|---|
| 1 | excessively well drained (fresh water area) |
| 2 | good drainage (fresh water area) |
| 3 | influence of fresh water but no flooding |
| 4 | fresh water flooding for short periods |
| 5 | fresh water flooding for long periods |
| 6 | permanent fresh water inundation |
| 7 | influence of salt water but no flooding |
| 8 | salt water flooding for short periods |
| 9 | salt water flooding for long periods |
| 0 | permanent salt water inundation |

were also collected in each area as described in Chapter 4.

(iv) FUTURE PROSPECTS

(a) Possible Future Commercial Development

In the context of this study, future development must be considered exclusive of the coniferous plantings and protection of native cypress pine stands presently being carried out by the N.T. Forestry Branch, and taken instead to refer to the possible development of native broadleaved forests. As mentioned earlier, sawlog production from these forests is limited, and the forest inventory programme undertaken in recent years was primarily designed for estimating pulpwood volumes. Stocker's (1972) comment quoted previously (page 21) underlines the potential use of the hardwood forests as a chipwood resource, and Forestry Branch personnel have prepared a number of internal reports on possible areas for chipwood projects.

(b) Proposed Further Inventory Work

Following the participation of Forestry Branch staff in a multidisciplinary study of the Alligator Rivers region in 1973, there was some expansion of forest inventory objectives to cover more general land use planning, and work was planned or in progress in several new areas such as the Adelaide River catchment and the King River area. These

December 1974. No large scale forest inventory field work was carried out during 1975 and 1976, but it is expected that work will recommence in the near future.

# CHAPTER 3 : THE APPLICATION OF TREE VOLUME TABLES TO NORTHERN TERRITORY FORESTS

The discussion in Chapter 1 demonstrated that tree volume tables provide the most practical method of estimating stand volume in tropical forests. In particular, the use of two-variable tree volume tables - where tree diameter and height are used to predict volume - or one-variable tables based on diameter, plus height-diameter relationships, appear to be the most appropriate.

## (i) APPLYING TREE VOLUME TABLES TO TROPICAL FORESTS

Foxworthy (1924) described forest inventory in tropical rain forest in Malaya using "... special volume tables which were prepared in British North Borneo and then adapted roughly to conditions in the Malay Peninsula." Since that time tree volume tables have been prepared and used for many tropical forest stands. The same volume tables referred to by Foxworthy were used during forest inventory in Sarawak in 1930 (Brunig, 1963). Many different volume tables were developed for Malaya over the years (Vincent and Sandrasegaran, 1965a), the most recent being a complete set of tables for the commercially more important rain forest species (Vincent and Sandrasegaran, 1965b), plus assorted volume tables for individual species, both natural and planted (Sandrasegaran 1966a, 1966b, 1967a, 1967b, 1969, 1972).

forests in many other areas, including Papua New Guinea (Shield, 1965), the British Solomon Islands (Bengough, 1966; Bengough and Burn-Murdoch, 1967), the Philippines (Chinte, 1969, 1971), Surinam (Silva Salazar, 1970), Rhodesia (Banks and Burrows, 1966) and Uganda (Kingston, 1970, 1971). This wide degree of usage confirms the conclusions reached in Chapter 1, despite the fact that tropical forest conditions can create problems in tree volume table application.

In tropical rain forest even the measurement of tree diameter can be difficult if the trees have high buttresses. The measurement of tree height or merchantable log length can also be difficult when dense undergrowth causes visibility problems. Various methods of measuring diameters above high buttresses have been used (Finlayson and Archer, 1964; Nicholson, 1965; Dixon, 1973; Nash, 1973a) and shortcut methods have been developed for measuring height (Haig, 1925; McArdle and Chapman, 1927; Archer, 1972). Nevertheless, the taking of such measurements is still far from easy, and ocular estimates have often been used - particularly for heights - to speed up field work. However, work in Papua New Guinea (Shield, 1967) and unpublished work by the author has shown that such estimates can suffer from serious bias, even when supplemented by occasional measurements to check the estimates.

Methods of developing localised height-diameter relationships to convert a two-variable volume table into one or more local volume tables have been discussed in Chapter 1.

Various stand height models were tested by Ker and Smith (1955, 1957), who pointed out that the stand height curve method is best suited to species or stands where variations in tree heights within diameter classes is low; however the variation in merchantable log length within a diameter class can be high for tropical forest species, as data for this study clearly demonstrate (see section (III) of this chapter).

Another common problem in tropical forests is the heavy fluting or other irregularities of cross section found in some rain forest trees, even above the buttresses. Work by Shield (1965) for Papua New Guinea and Finlayson and Tchanou (1975) for the Cameroons has shown that representative diameter measurements can still be taken in such cases, and, even when such irregularities occur in the sample trees, they may have only a minor effect on the overall volume estimate (Archer, unpublished).

## (II) SOME FACTORS AFFECTING APPLICABILITY

In addition to any difficulties which may occur in measuring the physical dimensions of tropical forest trees, there are a number of other factors which can affect the applicability of tree volume tables to the estimation of stand volumes in tropical forests. Some of these are discussed below.

(a) Representativeness of the Sample

Even the simplest forest inventory which uses tree volume tables is a form of double sampling, with the sample trees selected for volume table compilation representing the second phase of the sampling procedure. For this reason, the same degree of care should be taken to ensure a representative and statistically sound sample for the volume tables as for the first phase of selecting the inventory sampling units.

Many reports of tree volume table projects give little or no detail of the way in which the samples were collected. Others describe the data used as "representative trees of the crop" (Malik _et_ _al_., 1967), or "from as wide a variety of sites as possible" (Unwin and Bowling, 1951). In some cases sample tree measurements have been taken which may not be representative of the population to which they are later applied; for example, during commercial felling operations (Beers and Gingrich, 1958), from windthrow areas (Meyer, 1944) and in sawmills (Young, 1955). Thinnings have also been used to produce general volume tables for whole plantation crops (Sandrasegaran, 1969, 1970).

Bengough (1965, 1966) and Bengough and Burn-Murdoch (1967) describe the choice of samples in rain forest in the British Solomon Islands as including a given range of diameters, but otherwise arbitrary, with no deliberate rejection of defective trees. Honer (1965) refers to data collection from "a variety of sites, ages and cover types", and states: "In general, they represent the range of size classes attained by the species that were accessible to the samplers." And Nash's (1973b) account of an inventory of tropical rain forest in Surinam describes "...measurements on the major species from felled trees in as many diameter classes as possible."

Other workers have described somewhat more formal sampling prescriptions. Burley *et al.* (1972) during a national forest inventory of Cuba measured approximately 20 sample trees in each 2 cm diameter class within each major geographic stratum. Turner (1972) used data from Pennsylvania collected under a sampling scheme which collected each commercial species "...in direct proportion to its relative occurrence: (i) in each section of the [State], (ii) on each growing site, and (iii) in each timber type in which it occurred", with equally represented diameter classes over the normal diameter range of each species.

The need for representative and objective sampling may be acknowledged, but sampling schemes may be modified because of practical considerations. For example, Gerrard (1966) states:

> "Ideally, the location of plots should be based upon a random sampling scheme so that sampling errors will be equally distributed about zero. In practice, if efforts are made to sample a diversity of conditions roughly in proportion to the frequency with which such conditions occur the resulting data may be considered reasonably free of bias."

And Hindley (1973) describes the measurement of sample trees in rain forest in Sarawak, where "...the ruggedness of the terrain made felling and bucking extremely hazardous, and due to the remoteness of the survey areas, safety of the field crews had to override all other technical considerations, and crews were instructed not to attempt to fell and buck trees which might be dangerous to handle."

More objective sampling has been used in some cases. Sandrasegaran (1972) compiled tree volume tables using samples collected from randomised block experiments for Malayan mangroves, and Wong (1966) used samples from random 1 acre (0.4 ha) plots in Malayan rain forest.

Cases where volume tables have been compiled from truly random, unbiased samples of the population covered by an associated forest inventory do not seem to have been commonly reported in the literature, although the requirement is recognised. For example, FAO's (1973) "Manual of Forest Inventory" states that: "Geographic distribution of the plots for which the sample trees are selected should preferably be based on an objective sampling design either at random or systematic, or on a stratified random or stratified systematic design"; however the manual acknowledges that samples are often taken from large concentrated areas or from atypical locations for logistic or economic reasons.

(b) Variation Between Species

Tropical forests often include large numbers of different tree species. As Havel (1965) has observed, the tropical rain forest is the botanist's dream but the forester's nightmare: a simple plot enumeration becomes a major taxonomic exercise, and yet volume assessment without species identification gives no indication of the likely harvest.

Bowling (1951) compiled a volume table for eucalypt regrowth in Tasmania from all available data, irrespective of species. Tests of different species groupings showed very little variation between species, localities, site qualities or crown class groups. Spurr (1952) also produced composite volume tables for North American species, but found that percentage corrections were necessary in some cases for individual species. Gevorkiantz and Olsen (1955) produced similar tables for timber species in the Lake States, and suggested the use of percentage corrections for individual species where necessary, while Lea and Nyland (1969) developed a composite table for ten hardwood species in New York State which adequately fitted all except two species. A comparable statistical approach equivalent to the use of correction factors with a composite table has been developed by Bélanger and Cléroux (1973). However, Golding and Hall (1961) were unsuccessful in attempts to produce a composite table for three Canadian species, finding simple correction factors unsatisfactory.

Relatively little work has been done on differences between species for tropical forests. Shield (1965) produced a composite volume table for Papua New Guinea rain forest species, based on a sample of 461 trees from a number of localities, but pooled the data more out of expediency than from a detailed knowledge of the importance of differences betwen species. Wong (1966) also combined all species in each of several felled plots in Malayan rain forest in order to estimate total volume (bole plus branchwood) from diameter alone, but doubted that such an approach would be suitable for merchantable log volume because of inter-species differences. In the British Solomon Islands, Bengough (1965, 1966) and Bengough and Burn-Murdoch (1967) compiled separate local or one-variable volume tables for individual species of economic importance, but these covered only a small fraction of the total number of species present.

Hegyi (1965) measured 1425 rain forest trees in British Guiana and avoided the species problem by grouping the trees - irrespective of species - into taper index classes, based on the difference between diameters measured at breast height or above buttress and at 15 feet (4.6m) higher up. Hegyi proposed that taper index classes be determined initially within a forest district "... for each combination of diameter/height classes per species", and checked by only small subsequent samples for additional inventories. However he also noted that up to 200 species could occur within an area as small as 80 ha, which would necessitate a very large number of measurements to cover each diameter/height/species combination, even assuming that taper index was in fact strongly correlated with species. In addition, both Spurr (1952) and Carron (1968) state that it is difficult to improve the precision of estimate for a forest stand by merely assuming average taper values obtained by sampling.

As noted by FAO (1973), it is often not practical to produce separate volume tables for each different species during inventories of mixed tropical hardwoods, because of the large numbers of species present. Grouping of similar species to produce some form of composite volume tables is one practical alternative. Hahn (1973, 1975) grouped temperate forest species for the American States of Wisconsin and Missouri on the basis of similarity in bole form, and Barnard et al. (1973) describe volume tables for the northeastern United States where trees were grouped by "butt class" (based on the ratio between stump diameter and breast height diameter) and average Girard form class. Work in tropical forests wäs carried out by Vincent and Sandrasegaran (1965b), who produced 13 different volume tables for 38 different species or groups of species from Malayan rain forests. Their groupings were on the basis of abundance, tendency to grow in reasonably pure stands, and economic value.

Work on a somewhat more systematic grouping of species in tropical forests is discussed by Nash (1973b), who produced taper factors and taper regressions for 20 species from rain forests in Surinam; these were tested to see if data for individual species could be combined and new relationships recomputed, but no details are given on the final groupings achieved. Hindley (1973) measured 5010 sample trees in Sarawak, but only one species was sufficiently well represented to produce a separate volume table. The remaining species were initially divided into 18 groups based on similarity of wood properties, average cull factors, average diameter and geographic distribution. These were later combined into larger groupings after visual comparisons of plotted data and volume regressions.

(c) Variation Between Localities

As well as differences between species, differences between localities can also be important within individual species. Vincent and Sandrasegaran (1965b) examined their Malayan volume tables for bias, using a breakdown of the data by States and major forest reserves, and found aggregate deviations of up to 70%; however the larger differences may have been at least partly due to the chance variation of small samples. Wong (1966) found no significant differences between local (one-variable) volume tables for each of three randomly located plots in Malayan rain forest but, as mentioned earlier, was estimating total rather than merchantable volume. Bowling's (1951) finding of little difference due to locality in Tasmanian eucalypt regrowth has been noted earlier. Work in temperate forests by Barnard _et al_. (1973) involved testing for differences in Girard form class measurements within species due to location throughout five states in the USA: no significant differences were found.

Unpublished results from Papua New Guinea showed aggregate differences of 14% between two localities for rain forest trees less than 50 cm in diameter, and 13% between two other localities for larger trees, but both comparisons were based on limited data. Volume tables produced for the British Solomons by Bengough (1965, 1966) and Bengough and Burn-Murdoch (1967) were each for individual species from limited localities, and users were warned that the tables were not necessarily applicable to other areas. The authors describe a method to "test and relocalize" the tables "to suit a new area". Husch et al. (1972) also suggest a method of checking the applicability of volume tables, and Freese (1960, 1964) gives details of two different statistical tests for the significance of any differences found. These and other methods are discussed in Chapter 7.

## (iii) APPLICATION TO THE NORTHERN TERRITORY

In Chapter 2 it was concluded that either one-variable volume tables with associated stand height curves or two-variable tables were the most appropriate methods of estimating stand volumes in tropical forests. Visibility problems in tropical rain forest with a dense understorey of small trees usually make tree height measurements difficult and time-consuming, which favours the use of stand height curves fitted to a subsample of height measurements, together with local or one-variable volume tables. However, the tall open forest which is the dominant commercial forest type in the Northern Territory is generally on flat terrain and with little understorey, and this allows height measurements to be taken quickly and easily. Therefore the time taken to measure merchantable lengths for all trees in the sample is quite small, and is easily justified by the improvement in precision obtained with a two-variable volume table. This improvement is large, as can be seen from the wide range of merchantable lenghts occurring within diameter classes for the Northern Territory data (see stand tables in Appendix 2), which adds a substantial error component to estimated volumes when averages are used in place of actual heights. As discussed earlier (page 29), the use of stand height curves is most successful when there is a minumum of variation in height within diameter classes.

Trees in the tall open forest of the Northern Territory are in general not strongly buttressed or fluted as are many trees in tropical rain forests (including the limited areas of N.T. monsoon forest). The difficulties discussed earlier in obtaining representative diameter measurements in rain forests therefore do not usually occur, and height measurements are also easily obtained, as noted above. Problems of species identification are also considerably simplified by the limited number of large tree species occurring in the dominant forest type.

Representativeness of the data collected from the Northern Territory forest areas is discussed in Chapter 4, and the problems of limits to the data and extrapolation are dealt with in Chapter 9. The remaining problems of variations between species and localities are discussed in Chapter 7. The study in its entirety attempts to demonstrate that, given the conditions found in Northern Territory tropical forests, tree volume tables can be used to efficiently estimate stand volume.

# PART II : THE STUDY

## IIA. DATA

## CHAPTER 4 : DATA COLLECTION

The methods used in data collection for volume tables determine the extent to which the tables may be validly applied during forest inventory. This point has been discussed in Chapter 3 in the section covering representativeness of the sample, and its importance is further emphasised by the following comment from Grosenbaugh (1963) on the application of volume tables in the United States:

> "Unfortunately many volume tables were constructed by ...methods based on poorly selected samples. Even when volume tables were initially constructed from sample trees that may have been truly representative of a very specific tree population, ...the tables were biased by definition when applied to trees outside the specific population from which the sample was drawn - as they almost always were."

This chapter discusses the collection of sample tree data for volume tables in tropical mixed hardwood forests of the Northern Territory during the period 1967 to 1972, in the context of the present study.

### (i) THE STUDY AREAS

#### (a) Forest Types and Species Represented

The method of hardwood forest inventory used in the

Northern Territory has been described in Chapter 2. After stratification of each forest area on air photos a subsample of the photo plots was used as the inventory sample, but selection of the subsample was mainly confined to strata with some economic potential. For this reason not all of the broad forest types described in Chapter 2 are represented in the inventory sample for each area, and only the commonest tree species are adequately represented.

Sampling for volume table data was more restricted than for forest inventory. Table 4.1 shows the major forest types and species present in the sample for each of the forest areas shown in Figure 2.1 (page 17). These give a generally satisfactory cover of the majority of species and areas of economic interest, except for an inadequate coverage (and number) of "Other species".

The codes used for both species and locality (forest area) are given in Appendix 1.

(b) Available Data

Appendix 2 gives detailed stand tables for each common species in the sample from each forest area, plus figures for other species and all species combined. The poor representation of species other than the five common species shown in Table 4.1 - even in areas where they were included in the sample - made it impossible to use them in any meaningful analyses, and they were therefore excluded from

Table 4.1

Broad forest types and species represented in the data for each forest area.

| Forest area code (see Appendix 2) | | Tall open forest | | | | | Swamp forest | |
|---|---|---|---|---|---|---|---|---|
| | | E. miniata 01* | E. tetrodonta 02 | E. nesophila 03 | E. bleeseri 06 | Other species | Melaleuca spp. 68 | Other species |
| old style data (before 1970) | 02 | X | X | X | | X | | |
| | 03 | X | X | X | | X | | |
| | 07 | X | X | | | X | | |
| new style data (from 1970) | 011 | X | X | | | | X | |
| | 02 | X | X | X | | | | |
| | 0211 | X | X | X | | | | |
| | 022 | X | X | X | X | | | |
| | 031 | X | X | X | | | X | |
| | 07 | X | X | | | | | |
| | 091 | X | X | | X | | X | |

*The numbers shown under each species name are the species code numbers.

the present study.

The forest types described in Chapter 2 (from Stocker, 1972) are generally too broad for a useful stratification of Northern Territory forests for inventory purposes. A more detailed structural classification based on dominant height, crown closure and soil drainage was used instead (Table 9.1, page 130).

## (ii) DATA COLLECTION FOR VOLUME TABLES

Data collection for volume tables involves a number of considerations, including sampling methods, size of sample, and methods of measuring the volumes of sample trees. Sampling methods cover a very wide field; they are discussed in detail by Cochran (1963) for general applications, and more specifically for forestry purposes by Freese (1962). As noted by FAO (1973), sample tree selection for volume tables should preferably be based on an objective sampling design, and the discussion in Chapter 3 on representativeness of the sample has covered the way in which samples have been taken by different workers. Problems in adequately covering the full range of the data were also discussed.

A consideration of methods of measuring sample tree volumes partly overlaps the discussion in the section of Chapter 5 on tree volume computation. Methods of measuring both standing and felled trees are discussed by Carron (1968) and Husch _et al_. (1972). However if defect as well as gross bole volume is to be measured then sample trees must be felled, because non-destructive methods of measuring internal defect have been found unsatisfactory (Dowden, 1967). Although Paine (1968) and Hindley (1973) used techniques of boring for decay on standing trees, they were able to estimate defect only on the basis of measurements made on previously felled trees. A high incidence of defect in Northern Territory hardwood forests made it similarly necessary for measurements to be made on felled trees.

Methods of measuring stem volume are described by Husch et al. (1972) and Carron (1968). Those appropriate to volume measurement of merchantable boles in hardwoods include the sectional method, the graphical or taper curve method, and direct measurement by fluid displacement in a xylometer. The last method can only be used for small scale experimental measurements because of the time taken and the equipment required, and it has been used in this way by Young et al. (1967) and Dargavel and Ditchburne (1971) to test other methods and formulae used for calculating stem volumes. The graphical method gives reasonably precise results but is too time consuming for large numbers of sample trees. This leaves the sectional method or some similar method as the only practical alternative.

The number and lengths of sections to be used when measuring each tree bole have been investigated by some workers. Whyte (1971) showed that errors due to incorrect assumptions of the shapes of stem sections become negligible if the differences between the end diameters of each section is kept within certain limits, and Young et al. (1967) found the smallest errors in volume estimate for short sections. Hegyi (1965) compared measurements over only three sections with more frequent measurements for tropical hardwoods in British Guiana and found no significant differences in the volume estimates.

The method of measurement used for the Northern Territory data was determined well in advance of the present study and is described in the next section. The problems of which geometric shapes to assume and which formulae to use for volume calculation from the data are discussed in Chapter 5.

## (iii) DATA COLLECTION IN THE STUDY AREAS

### (a) Sample Selection

Two different methods were used for collecting tree measurement data for hardwood volume tables in the Northern Territory. The earlier method, used before 1970, involved three-phase sampling. The first phase consisted of photo plots, interpreted as described in Chapter 2 to provide estimates of the proportions of different forest type strata in each forest area. The second phase consisted of a subsample of the photo plots for field measurement during forest inventory, and the third phase was a further subsample of the inventory plots on which all trees were felled and measured. This method of sampling was objective and statistically valid, but had the disadvantage that the larger tree sizes were poorly represented in the sample, which is noted by FAO (1973) as a common problem in mixed hardwood forest.

The later method of data collection, used from 1970 onwards, prescribed that equal numbers of trees be collected from each diameter class in the population: the use of similar sampling schemes by other workers has been noted in Chapter 3. Measurement of felled trees in a subsample of the inventory plots was discontinued because of the problems of locating sufficient numbers in each size class, and subjective sampling was employed to give a reasonable coverage of forest types for the important species. In addition, a maximum diameter was apparently applied in each area, above which no trees were selected.

The implications of this change in sampling method are discussed later.

(b) Individual Tree Measurements

The following information was recorded for each sample tree:

locality

forest type

species

merchantability

d.b.h.

stump height

pulpwood log length

sawlog length

The log length selected by the measuring team determined the gross merchantable volume of each tree. The length was taken from top of stump to a limiting point such as crown break or some major bend or defect.

Quartile measurements were taken along the merchantable log after felling, for diameter over bark (d.o.b.), bark thickness, and diameter of internal defect as measured at each measurement point after cross cutting. Under the old style method the measurements were taken at the exact quartile points, i.e., at the butt, one quarter log length, half way, three quarters log length and at the top of the log. This was changed under the newer system to allow measurement points to be moved away from unrepresentative points (e.g., spikes or swellings) if necessary, and the length of each section was recorded. Other differences were - apart from changes in layout of the measurement recording sheets - that the diameter of internal defect was recorded to the nearest 0.1" (0.3cm) under the old system but to the nearest 1" (2.5cm) under the later system, and that total tree height was also omitted from old style measurement sheets because it was readily available from the inventory record for each plot.

(c) Application to the Study

The differences in measurement techniques between old and new style data are so minor as to have no significant effect on comparability. The strict quartile convention applied to the older data may have inflated the variance of sample tree volumes to some degree, but both validation checks and examination of merchantable stem profiles (Chapter 5) indicated that all of the data showed frequent large irregularities in bole shape. Additional variation introduced by some unrepresentative d.o.b. measurements would therefore have been relatively minor, especially since measurement points were rarely moved from the quartile position for the new style data.

The differences in methods of sample selection are more serious. While the old style data represent an objective and representative subsample of the population covered by each associated inventory, this is not the case for the new style data. However the majority of the data was collected under the newer system which covers a somewhat wider range of species and forest types than the old style data.

It was decided to incorporate the new style data into the study, even though there would be unknown errors in applying the results to individual forest inventories. It was hoped that the results could at least provide the basis for further work.

# CHAPTER 5 : INITIAL DATA PROCESSING

All Northern Territory forest inventory data were originally stored on magnetic tape at the University of Adelaide Computer Centre. Copies of the tree measurement data and the old style inventory field plot data were transferred to the Univac 1108 computer at the Australian National University in March 1975. Old style data were converted to new style format and total tree heights missing from the old style data were obtained from the inventory field plot records. Unmerchantable trees in the old style data - which were recorded but not fully measured - were deleted.

## (i) CHECKING THE DATA

Checking the data is an essential part of volume table construction. A small number of serious errors can noticeably bias the relationships obtained and lead to incorrect estimates of stand volume from forest inventory. The additional step of testing the validity of the data is usually minor when compared with the time and money spent on an entire operation.

All of the data used in the study were originally processed by edit programs written by Mr W.M. Pearce of the University of Adelaide Computer Centre. The programs checked for illegal characters, invalid codes and anomalous measurements, and the results were sent back to Forestry Branch staff in Darwin for corrective action. Records with gross errors such as faulty coding or missing measurements were either modified or deleted, while sample trees with less serious anomalies (e.g., negative taper) were merely flagged to be ignored but not removed from the data.

Because of this preliminary checking it was expected that there would be no major errors in the data. However, to guard against possible corruption of the data during transfer to the Univac computer and to cover some possible anomalies not tested for in the original edit programs, it was decided to edit all of the data again.

(a) Validation Tests

Manual and graphical checking of data for tree volume tables in Tasmania is described by Unwin and Bowling (1951). Carron's (1968) description of the sectional method of measuring stem volume includes the suggestion that measurements up the stem be checked for sensible trends. Turner (1972) describes a computer program for calculating sample tree volumes which checked for errors in the data.

The program used for validating the data on the A.N.U. computer duplicated some of the tests in the programs used in Adelaide, modified others and included some new tests. It tested for illegal characters and invalid coding, and checked that measured values were reasonable. Acceptable limits of variation were initially prescribed in the light of past experience with tree measurement data from tropical rain forest in Papua New Guinea, but it was found that Northern Territory data showed considerably more variation. For example:

- bark thickness measurements along the bole of a single tree varied up to 10 times from the smallest to the largest value. This was not entirely surprising for _E. miniata_ because of its heavy stocking of rough bark, but had not been expected for other species. Measurement errors were an unlikely source of the variation because bark thicknesses were usually measured at the ends of cross cut sections rather than with bark gauges.

- underbark taper between consecutive diameter measurements varied from decreases of as much as 75% in diameter between consecutive measurements up the stem (usually associated with the butt section) to increases in diameter (i.e., negative taper) of as much as 50%. This can be seen from the stem profiles shown in Figure 5.1, bearing in mind that they illustrate basal area against height and therefore exaggerate percentage differences in diameter.

- the measured value of d.b.h. was often very different from the expected value obtained by interpolating from the sectional d.o.b. measurements. This can also be seen in Figure 5.1.

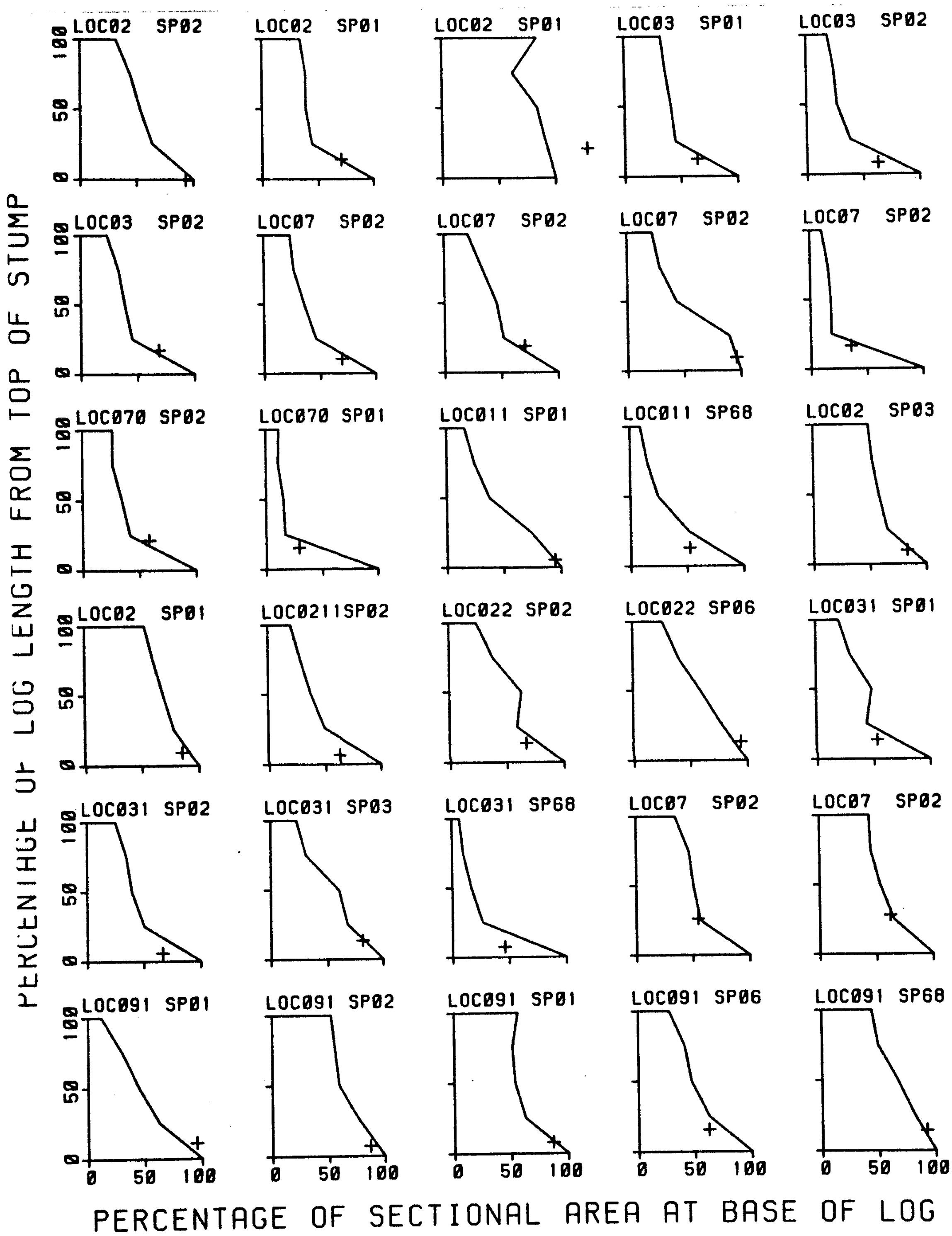
The general irregularity of the data was a source of considerable concern and it was decided to further investigate some aspects of the variation. Because tree volume varies approximately as the square of diameter, volumes predicted from volume tables are highly sensitive to errors in d.b.h. The apparent irregularities in d.b.h. were therefore chosen for initial investigation. This had the added advantage that comparison of actual and interpolated d.b.h. would also provide some information on variation in taper for the lower part of the tree.

The position of d.b.h. relative to the sectional measurements varied with log length and stump height. It most commonly fell in the butt section between the first and second d.o.b. measurements, but also occurred above the second measurement in a small percentage of cases. Examination of stem profiles of a subsample of the data (Figure 5.1) indicated that, although tree shape was very irregular, the butt section was generally concave while the next section apparently varied from convex to slightly concave, as best as could be judged from the small number of diameter measurements taken for each tree. A conical shape (i.e., somewhat concave for a plot of sectional area against height) was used for interpolation in the edit program, as a rough weighted average of shape for the two sections of the tree where d.b.h. occurred. However this was not considered adequate for a closer investigation, and a program was written to compare actual d.b.h. with values interpolated from a paraboloid, cone, neiloid and hyperboloid (in increasing order of

Figure 5.1

Stem profiles for a subsample of the data. Both overbark sectional area and height above top of stump are expressed in percentages.

Relative position of d.b.h. shown thus: +



convexity) for the butt section of each tree. A paraboloid was assumed as an approximate average for the second section, but this had little effect on the results because of the small percentage of d.b.h. measurements occurring above the second d.o.b. position. Deviation of actual d.b.h. from interpolated was expressed as a percentage of the interpolated value, and frequencies within 2 percent classes of deviation were plotted as histograms for each species within each locality.

Variation between species and localities considerably exceeded the relatively small changes in mean deviation between the different geometric shapes assumed for interpolation. A summary of the results for a neiloid is given in Table 5.1; the corresponding results for a paraboloid were about 1-2% lower, and about the same amount higher for a hyperboloid. The deviations were found to show a disturbingly consistent positive bias for the old style data and an even more consistent negative bias for the new style data. However it was not possible to account for these trends in terms of a different geometric shape for the butt section of the tree, because of the relatively small changes in deviations calculated from alternative shapes. The type of shape required to account for each bias would have been so convex for the old style data and so concave for the new style data as to be most unlikely, even apart from the difficulty of justifying very different shapes for sample trees collected from overlapping or adjacent forest areas on different occasions. After a careful review of both the old and new

Table 5.1

Mean deviations of actual d.b.h. from interpolated d.b.h. for separate species within localities. The interpolation assumes a neiloid for the butt section of each tree, and the deviation is expressed as a percentage of the interpolated value. Numbers shown in brackets at the ends of some lines of the table are numbers of trees excluded as outliers.

| Locality | Species | No. of samples | Mean dev.(%) | Max.(%) | Min.(%) | |
|---|---|---|---|---|---|---|
| 02 | 01 | 150 | +5.22 | +35.31 | -18.75 | |
| (old) | 02 | 108 | +3.03 | +20.59 | -18.23 | |
| | 03 | 88 | +9.54 | +31.90 | -14.41 | |
| 03 | 01 | 96 | +0.90 | +49.33 | -14.90 | (1) |
| (old) | 02 | 103 | -0.24 | +22.18 | -21.14 | |
| | 03 | 72 | +7.52 | +30.48 | -14.99 | |
| 07 | 01 | 87 | +2.22 | +58.06 | -38.25 | (1) |
| (old) | 02 | 421 | -0.10 | +36.02 | -42.01 | (1) |
| 070 | 01 | 42 | +10.11 | +33.14 | -12.38 | |
| (old) | 02 | 157 | +1.41 | +24.72 | -24.21 | |
| 011 | 01 | 65 | -3.41 | +11.04 | -16.56 | |
| | 02 | 96 | -7.65 | +4.69 | -17.22 | |
| | 68 | 108 | -8.94 | +17.90 | -25.75 | |
| 02 | 01 | 57 | -1.62 | +8.71 | -12.67 | |
| | 02 | 45 | -3.02 | +5.42 | -11.74 | |
| | 03 | 54 | -1.75 | +8.35 | -11.05 | |
| 0211 | 01 | 54 | -6.24 | +4.99 | -15.36 | |
| | 02 | 54 | -7.73 | -0.10 | -15.27 | |
| | 03 | 54 | -5.67 | +8.41 | -15.00 | |
| 022 | 01 | 44 | -3.84 | +6.97 | -13.70 | |
| | 02 | 44 | -8.18 | +1.47 | -17.88 | |
| | 03 | 44 | -6.92 | +2.97 | -17.24 | |
| | 06 | 44 | -2.63 | +9.22 | -12.35 | |
| 031 | 01 | 121 | -2.94 | +13.76 | -21.48 | |
| | 02 | 111 | -5.96 | +9.19 | -18.49 | |
| | 03 | 126 | -3.36 | +22.66 | -21.35 | |
| | 68 | 131 | -11.73 | +11.77 | -27.95 | |
| 07 | 01 | 80 | -0.83 | +9.88 | -15.13 | |
| | 02 | 168 | -4.80 | +14.82 | -22.87 | |
| 091 | 01 | 157 | -2.97 | +9.10 | -25.42 | |
| | 02 | 156 | -5.55 | +7.16 | -18.57 | |
| | 06 | 156 | -5.75 | +9.82 | -26.10 | |
| | 68 | 155 | -6.45 | +25.57 | -19.80 | (2) |

style measurement methods - and consultations with former officers of the N.T. Forestry Branch which provided no obvious reasons for these results - it was decided that there was no alternative to using the data in their present form, even though the apparent biases in d.b.h. would almost certainly affect subsequent analyses. Because of this uncertainty, the d.b.h. measurements were not included among the diameter measurements used to define the shape of each sample tree.

The range of deviations between actual and interpolated d.b.h. can be seen from the maximum and minimum figures given in Table 5.1. However, the plotted histograms showed that the individual deviations generally formed a continuous and approximately normal distribution for each species. This made it difficult to reject even relatively large deviations as due to measurement error - except for the few outliers discussed in the next section - and confirmed the impression obtained from the results of the data editing program that the sample trees showed very large variations in shape.

In the light of these results the other sample tree measurements which showed large variations - such as bark thickness and underbark taper - were re-examined, and it was found equally difficult to single out individual samples which were not part of a wide and continuous range of variation. The data were therefore accepted as being highly variable and, except where obvious measurement errors or omissions were detected as discussed in the next section, the samples flagged as anomalous by the edit program were accepted.

(b) Treatment of Anomalous Values

Anomalies flagged by the edit program were classified into two types. The first type was assumed to be due to measurement error or omission and the second type was taken as part of the wide but presumably normal variation found in the data.

Anomalies of the first type occurring in the old style data included obvious missing or inconsistent measurements. Many of the trees previously flagged as anomalous in the old style samples were in fact accepted as part of the wide variation in the data, as were both of only two trees flagged throughout all of the new style measurements. Re-editing of the data was therefore found to be justified in view of the apparent inconsistencies and oversights in the original editing.

Anomalies of the second type, resulting from the wide variation in the data, were found for several measured values including bark thickness, taper and d.b.h. All were accepted, as discussed in the previous section, except for a small number of trees with d.b.h. values which were obviously outliers. Because of the sensitivity of volume estimates to errors in d.b.h. some extra time was spent on detecting possible errors in the d.b.h. measurements.

Detection of outliers is discussed by Dixon and Massey (1957), Snedecor and Cochran (1967) and others. A criterion suggested by Nash (1965) for forestry applications is the rejection of data with deviations greater than or equal to 2.5 standard deviations from the mean; however this criterion rejects 1.24% of the data from a normal population and seems unduly harsh for large data sets. An alternative criterion was used to avoid excessive filtering of the data: observations were excluded only if their deviations had an associated probability of less than (0.05/n), where n is the number of observations for each species from a given locality. A total of 5 outliers were excluded in this way from a total of 3525 observations.

## (ii) COMPUTING SAMPLE TREE VOLUMES

The method used for computing the volumes of sample trees is fundamental to the production of satisfactory tree volume tables. Any inadequacies or bias in volume estimates for the input data are reflected in the final tables. Because of the small number of diameter measurements taken for each sample tree in the Northern Territory data it was considered doubly important to ensure that the method used was as free from bias as possible.

(a) Methods of Tree Volume Computaion

Husch *et al*. (1972) describe the way in which the merchantable boles of hardwood trees are assumed to resemble frusta of neiloids, cones or second degree paraboloids and give the formula for calculating volume in each case. The use of Huber's and Smalian's formulae which assume a paraboloid, and Newton's prismoidal formula which requires no underlying assumption of shape, are described by Carron (1968) and Husch *et al*. (1972). The latter authors recommend that Smalian's formula be used for short sections if possible, because of the large potential error with shapes other than a paraboloid, and suggest the use of either Newton's or Huber's formula for longer sections. However they note that Newton's formula does not give good results for excessively concave butt sections.

Although a second degree paraboloid is often assumed for sections of both coniferous and hardwood stems - except for the butt section which may be treated as a neiloid - it is not always appropriate, even for the normally more regular bole shapes of conifers. Kloos *et al*. (1967) found that for red pine in Pennsylvania a fourth degree polynomial was needed to yield an adequate approximation to stem shape, and that volumes calculated were consistently higher than with Smalian's formula. For tropical hardwoods, FAO (1973) highly recommend the use of Newton's formula, especially for long sections, because of its applicability to shapes other than a paraboloid.

Computing volumes of butt sections of the stem can be a problem if the shape of the lower part of the bole is excessively concave. Although a neiloid is commonly assumed, work with taper curves (Matte, 1949; Bruce et al., 1968) has produced considerably more complex curves, and Ormerod (1973) used a discontinuous step function to allow for the different shape in the butt section of Canadian trees. Taper curves are further discussed in Chapter 6.

A simple shape which does not seem to have been discussed in the literature, and which is applicable to butt sections more concave than a neiloid, is the hyperboloid. The formula for the volume of a frustum is simpler than for a neiloid:

$$V = h\sqrt{(aA)}$$

(where V is the volume of the frustum, h is the length, a is the cross sectional area at the top and A the cross sectional area at the base). Interpolation of diameter or sectional area is also simpler in that the reciprocal of sectional area, or diameter squared, is linear with height.

A further potential problem with computing stem volumes of sample trees occurs with the underlying assumption that the cross sections are circular. As discussed by Carron (1968) and Husch et al. (1972), any major departure from a circular shape will lead to bias in calculated sectional area. The use of diameter tape measurements rather than measurements taken with calipers will lead to some degree of overestimate in sectional area and therefore in volume.

However, as noted in Chapter 3, Northern Territory hardwoods generally do not have the heavy buttressing or fluting often found in rain forest hardwoods, and the assumption of circular cross sections would not have introduced significant bias.

(b) Variation in Shape of Sample Trees

When compared with conifers, broadleaved trees are usually much more variable and irregular in shape. As Assman (1970) has noted:

> "As compared with the many diverse and, in some cases, bizarre outlines of broad-leaved trees, conifers present regular forms..."

The irregular and variable bole shapes of the sample trees can be judged from the earlier discussion in this chapter on editing of the data, and from the subsample of stem profiles shown in Figure 5.1. For the sake of comparison, the profiles have been plotted with sectional area expressed as a percentage of butt sectional area against percentage of log length. Apart from the general observations that some degree of buttswell is almost always present and generally confined to the first section, and that the remainder of the bole generally shows a rough overall approximation to a paraboloid (i.e., approximately linear), it is difficult to detect much consistency in shape. Stem profiles of additional samples were plotted for some of the localities to check the variation within and between species, but no real consistency was found. The degree of buttswell noted in some cases was such that the butt section would have been considerably more concave than a neiloid, but again this was found for several species and inconsistently for each.

The possibility was considered that tree shape was correlated with stand conditions and therefore varied with forest type. However it was not considered worthwhile to initially produce sufficient stem profiles to cover the full range of species and localities. It was expected that if any consistent trends were present they would show up in later analyses and that if this occurred the problem could then be re-examined.

(c) The Volume Computation Program

A computer program for calculating tree volumes was produced by Stage et al. (1968). The program used Smalian's formula for each section except where the diameter at the top of a section exceeded the lower diameter, in which case the volume was calculated for a frustum of an inverted cone. A volume calculation program described by Turner (1972) used Newton's formula for lower sections and Huber's formula for upper sections.

In the case of the Northern Territory data the possible methods of volume calculation were limited by the quartile arrangement of diameter measurements. Newton's formula could not be used in cases where diameters were unequally spaced, either as originally measured or as subsequently interpolated for assortment volumes. Volumes were therefore calculated for separate frusta between each pair of measurements, assuming a neiloid for the butt section and a parabolic shape for the remainder. Although this did not seem to be a fully satisfactory expression of the range of bole shapes in Figure 5.1 it was not possible to develop a better alternative with the small number of measurement points for each tree.

Gross merchantable underbark volume was calculated from the measurements recorded for each tree. For some of the smallest trees the volumes included stem sections of very small diameter; for this reason volumes to various small end d.u.b.s were also calculated by interpolation, together with estimates of internal defect volume.

Two other values were also produced for each sample tree, for possible use in later analyses. An average underbark to overbark sectional area ratio at breast height was calculated from the two nearest diameter and bark thickness measurements, weighted by their closeness to breast height. And an average rate of underbark taper (in square metres of sectional area per metre of length) was calculated for the upper three sections of each tree.

# PART IIB : DEVELOPMENT OF VOLUME MODELS

## CHAPTER 6 : METHODS OF VOLUME TABLE CONSTRUCTION

A number of different methods of constructing volume tables are available:-

### (i) GRAPHICAL METHODS

Graphical methods of volume table construction, such as the fitting of harmonised curves and the use of alignment charts, are described by Graves (1914), Chapman (1921), Carron (1968) and others: they will not be discussed in detail here. For while graphical methods have some advantages (Spurr, 1952; Cromer and Carron, 1956), the disadvantages far outweigh them. The disadvantages of graphical methods are that they are subjective and require considerable experience to achieve satisfactory results (Spurr, 1952). Finally and most importantly, there no statistically valid methods of determining the precision of volume estimates given by the tables.

### (ii) STATISTICAL METHODS

The advantages of statistical methods of volume table construction include objectivity and that statistically valid estimates of precision can be obtained. Statistical methods include the fitting of linear and non-linear regressions to tree measurement data by regression analysis. Tree volume tables can be constructed in this way from the direct fitting of tree volume equations or indirectly from taper functions.

(a) Taper Functions

Taper functions are used to express the average stem profile of a population of trees. The usual type of relationship expresses relative diameter along the stem as a function of relative height. Once the relationship is determined the volume for a given d.b.h. and total height can be calculated as a solid of revolution.

Behre (1923, 1927) developed taper functions for a large number of Northern Hemisphere conifers and also referred to earlier work by Höjer and Jonson. He used a simple hyperbola of the form

$$y = x/(b_0 + b_1x)$$

where y is the ratio of the diameter at distance x from the tip to "normal" d.b.h., the distance x being expressed as a percentage of total height above breast height. However, like the other workers he cited, Behre achieved this degree of simplicity only by graphically eliminating the effect of buttswell from each stem profile to obtain "normal" rather than actual d.b.h.

The complexity of stem shape was allowed for by

Matte (1949) with a taper function for loblolly pine which had an inflection point to simulate buttswell. His equation was

$$y^2 - x^4 = b_0(x^3 - x^4) + b_1(x^2 - x^4)$$

where x and y were similar variables to those used by Behre, except that actual rather than "normal" d.b.h. was used in y.

Bruce et al. (1968) developed an extremely complex taper function in an attempt to accurately reflect the average shape of red alder, with terms in diameter, height and relative height (up from breast height, rather than down from the tip) to the powers 1.5, 3, 32 and 40 respectively. However Kozak et al. (1969) used a simple parabolic function of the form

$$y = b_0 + b_1x + b_2x^2$$

which they found to be only slightly less accurate than far more complex equations. Their simple equation was used by Demaerschalk (1971) to produce tree volume equations and factors for obtaining volume estimates from point sampling.

The more complex methods of multivariate analysis of tree taper used by Fries (1965) and Fries and Matern (1965) were also found by Kozak and Smith (1966) to be little better than the use of simple functions, sorting and graphical methods for analysis of tree taper. Grosenbaugh (1966) also suggested in a study of stem form that the use of complex functions to define stem shape was unwarranted and lacked generality. Demaerschalk (1972, 1973) and Munro and Demaerschalk (1974) also advocated the use of relatively simple taper functions.

Taper regressions were used for rain forest species in Surinam by Nash (1973), and by J.E. Opie (pers. comm.) for eucalypts in Victoria. According to Bruce _et_ _al_. (1968) the advantages of developing taper functions lie in the ease of obtaining volumes to different small end diameters and in the internal self-consistency of these different estimates. As noted by Grosenbaugh (1966), the development of complex taper functions may lack generality; however a simple function used by Kozak _et_ _al_. (1969) showed systematic bias at different heights and would have yielded biased estimates of assortment volumes.

Taper functions are obviously most applicable within individual species of relatively uniform shape, and most successful when there are sufficient measurement points on each tree to adequately define the stem profile. Because of the highly variable stem shapes found in the Northern Territory data and the small number of diameter measurements taken on each tree the use of taper functions was not adopted. It was assumed that less error would arise from using the actual measurements, and assuming a particular geometric shape between only two measurements at a time, than from attempting to fit a single continuous function to the small number of points on each profile.

(b) Tree Volume Equations

Two-variable tree volume equations express tree volume as a function of diameter and height, with coefficients estimated by the method of least squares. Many simple and multiple linear regression models have been developed, and more recently non-linear regressions have also been used.

Linear Regression

Construction of two-variable tree volume tables by least squares involves the fitting of regression equations with volume (or some function of it) as the dependent variable and various functions of diameter and height as the independent variables. Linear regression has beeen used for volume table construction since Schumacher and Hall (1933) first developed "... a theory bearing on the mathematical expression of tree volumes". Some of the more commonly used tree volume equations include:

- logarithmic (Schumacher and Hall, 1933):

$$\log V = b_0 + b_1 \log D + b_2 \log H$$

- combined-variable (Stoate, 1945; Spurr, 1952):

$$V = b_0 + b_1 D^2 H$$

- Australian (Stoate, 1945):

$$V = b_0 + b_1 D^2 + b_2 H + b_3 D^2 H$$

Regression models can also be produced by automatic selection from a set of variables to develop the equation of best fit. Draper and Smith (1966) list the following methods: combinatorial screening of all possible combinations (e.g., Grosenbaugh, 1958, 1967; and more recent developments such as Furnival and Wilson, 1974); backward elimination of non-significant variables from a complete model (e.g., Kozak and Smith, 1965; Martin, 1971); forward selection of the most significant variables to build up the model "from below" (e.g., Freese, 1964; Lawrence, 1965); and stepwise regression - again building up from below, but reexamining each variable at every stage to test the efects of later variables on those introduced earlier. The last method is recommended as the best by Draper and Smith, but they and others (e.g., Freese, 1964; Kozak and Smith, 1965) emphasise the dangers of excessive reliance on automatic selection procedures: they stress the need for judgment in the initial selection of variables and critical examination of the models produced.

## Statistical Assumptions in Linear Regression

The mathematical basis for the method of least squares is given by Wilks (1962), Draper and Smith (1966) and others. The underlying assumptions are (Freese, 1964, 1967):

(i) the variance of the dependent variable is the same at all levels of the independent variables;

(ii) the errors, or departures from the regression, of the sample observations are independent;

(iii) the variation of the dependent variable about the regression surface follows a normal distribution (necessary only for hypothesis testing).

Assumption (i). The assumption of homogeneous variance or homoscedasticity is almost always invalid with volume table data. Trees with larger diameter and height measurements usually show more variation in volume than trees of smaller dimensions; even where the coefficient of variation is similar for both small and large trees the level of variation in absolute terms is still considerably different. Methods of testing for heterogeneity of variance are discussed in Chapter 7.

Weighted regression analysis can give more precise estimates of the coefficients than ordinary unweighted regression fitting, when the variance is heterogeneous (Freese, 1964). Unweighted regression analysis under these circumstances may also produce biased estimates of volume for the smallest trees in the data (Gibson and Webb, 1968; Evert, 1969b). Weighted regression analysis involves weighting each observation by the inverse of its estimated standard deviation about the regression surface. The method is described by Freese (1964), Cunia (1964) and others. Application to the Northern Territory data is discussed in Chapter 7.

Transformations to the dependent variable (e.g., log (V) used in place of V) can also be used to improve the homogeneity of variance. However, as discussed in Chapter 7, transformations of this type may introduce bias into the model.

Assumption (ii). The assumption of independence of errors may also be invalid for tree volume data in some cases, especially where the measurements in the sample are taken on clusters of trees within plots, rather than on individual trees randomly distributed throughout the population. Observations on contiguous trees may exhibit some degree of intercorrelation, because of similar site factors or genetic similarities. Model inadequacy or misspecification (Wonnacott and Wonnacott, 1970) may also cause systematic departures from the regression surface which are serially correlated. All serial correlation can be considered to result from misspecification, in that it results from some source of variation not allowed for by the regression model, but it may not always be possible to quantify this variation and include it in the model.

If ordinary least squares methods are applied in the case where significant serial correlation is present the estimates of the regression coefficients will have larger sampling variances than for completely random data (Ezekiel and Fox, 1959). The precise forms of the F-tests derived for linear regression models will also be invalid (Johnston, 1963): this point is particularly relevant to the covariance analyses described in Chapter 8. Methods of testing for serial correlation are discussed in Chapter 7.

Suggested approaches with serially correlated data include corrections to the error formulae used for completely random data, or the use of first differences in place of the original values (Ezekiel and Fox, 1959). The simplest approach for tree volume data exhibiting significant serial correlation - assuming that it cannot be eliminated by improving model specification - is to randomly cull the data to reduce any effect of clustering which may be present.

Assumption (iii). A normal distribution of residuals is not required for unbiased estimates of the regression coefficients, but is required for computing confidence limits with the usual error formulae and for carrying out F-tests (Freese, 1964; Draper and Smith, 1966). Since this assumption is also highly relevant to the subsequent analyses, methods of testing for significant departures from normality are described in Chapter 7.

When the distribution is not normal, a suitable transformation of the dependent variable can sometimes be used to achieve normality (Acton, 1959). However this can produce bias in a predictive model, as discussed in Chapter 7. According to Sokal and Rohlf (1969), the consequences of nonnormality are not too serious and only a very skewed distribution would have a marked effect on the significance level of an F-test.

## Non-linear Regression

Linear regression models must be linear in the parameters:

$$Y = b_0 + b_1X_1 + b_2X_2 + \dots + b_nX_n$$

Non-linear models are non-linear in the parameters, as in the example:

$$Y = e^{(b_0 + b_1X)}$$

Complex linear regression models may in some cases represent approximations to a simple functional relationship of non-linear form. Draper and Smith (1966) state: "When we are led to a model of non-linear form, we should usually prefer to fit such a model whenever possible, rather than to fit an alternative, perhaps less realistic, linear model."

An early example of a non-linear model for volume table construction was Schumacher and Hall's (1933) basic equation:

$$V = b_0D^{b_1}H^{b_2}$$

Because this model is of the type described by Draper and Smith (1966) as "intrinsically linear", it can be converted to linear form by a logarithmic transformation to give the volume equation mentioned earlier:

$$\log V = \log b_0 + b_1 \log D + b_2 \log H$$

The addition of a constant term to the basic model (e.g., Turner, 1972) gives a form which is intrinsically non-linear and which cannot be transformed into a linear form:

$$V = b_0 + b_1 D^{b_2} H^{b_3}$$

Models of this type cannot be fitted by linear regression analysis. Instead, the parameters must be estimated by iterative methods (Williams, 1959; Draper and Smith, 1966), as discussed in Chapter 8.

Non-linear regression theory is not as well developed as linear regression theory. Development has concentrated on improving methods of fitting regressions (Marquardt, 1963; Bard, 1967) and on confidence intervals of the estimated parameters (Beale, 1960; Draper and Smith, 1966), but the literature does not seem to deal with topics such as confidence intervals for predictions or general hypothesis testing. It was decided to use linear regression methods for preliminary model development and testing for differences within the data, and to introduce and evaluate non-linear regressions only during final model development.

The application of linear regressions is discussed in Chapter 7 and of non-linear regressions in Chapter 8.

# CHAPTER 7 : LINEAR REGRESSION MODELS

Analysis of the Northern Territory data involved the double problem of how to subdivide the data and which regression model or models were most suitable. The problems were interdependent in that final regression models could be developed only after the data groupings had been established, but at the same time the testing necessary for determining the groupings required the use of regression models. The approach taken in this study was to develop a linear model which gave a reasonably good fit to the data, use this model to determine data groupings, and then develop final models on these groupings.

## (I) DEVELOPMENT OF PRELIMINARY MODELS

The choice of the appropriate model is the most important decision in regression analysis. As noted by Draper and Smith (1966), the use of an inappropriate regression model will introduce bias, even when the underlying assumptions of homogeneous variance and independent, normally distributed errors are satisfied. In fact, as discussed later, model inadequacy can of itself contribute to the violation of these assumptions.

Model development for the Northern Territory data involved more than the production of a single satisfactory model for one homogeneous data set. Some degree of generality across all data sets was desirable to simplify comparisons between species and localities.

The data were partitioned first by locality, and then by species within each locality. It was assumed that if there were in fact no significant differences between species, or between localities within a species, this would show up in later analyses and the data could then be appropriately recombined.

(a) Linear Regression Models

General discussions of model development are given by Freese (1964) and Draper and Smith (1966). Regression models for volume tables have been developed by a number of methods, including attempts at logical development from known relationships, comparative trials of different models from the literature and the use of computer programs to select the equation of best fit from a number of independent variables.

Models proposed by Schumacher and Hall (1933), Stoate (1945) and Spurr (1952) were mentioned in the previous chapter. Additional models proposed by other workers include:

$$V = b_1 D + b_2 D^2 + b_3 DH + b_4 D^2 H \qquad \text{(Meyer, 1944)}$$

$$V = b_0 + b_1 H + b_2 D^2 H + b_3 H^2 + b_4 D^2 H^2 \qquad \text{(Shield, 1965)}$$

$$V = D^2/(b_0 + b_1/H) \qquad \text{(Honer, 1965)}$$

Other models were developed by different workers. Spurr (1952) used North American data to test 13 different equations proposed by different workers, Bride (1961) tested

15 different equations on Nigerian data, and Golding and Hall (1961) tested 25 equations with Canadian species. One simple model which performed consistently well was the combined-variable equation. Beers and Gingrich (1958), Simpfendorfer (1959) and Golding and Hall (1961), after comparative tests of different models, all recommended the combined-variable as combining high precision with ease of use, and Barnard et al. (1973) found it best for species from the north-eastern United States. It was the only model used by Smith and Breadon (1964) for British Columbia species, and by Allan et al. (1974) for small trees in northern Idaho. Hindley (1973) chose the combined-variable model for tropical rain forest species in Sarawak after "extensive prior testing of various regression types".

(b) Models for the Northern Territory Data

A preliminary model was required which would provide a reasonably good fit to all data sets. The combined-variable equation was chosen as the simplest model likely to perform well, in view of results reported in the literature. At the same time it was realised that this model would not necessarily be adequate, because of possible curvilinearity introduced by the use of merchantable volume rather than total volume (Spurr, 1952). Therefore a relatively simple alternative model was developed for comparative testing. Starting with the combined-variable model, corrections were made to allow for the effect of using merchantable length and merchantable volume, instead of total height and total volume. Tentative correction terms were developed as follows:

(a) assume a correction to merchantable height, to allow for it ending at an unknown small end diameter instead of at the top of the tree: $(H + c)$

(b) assume that this correction term is related to the unknown small end diameter, taking a linear relationship for simplicity: $(H + b''_0 + b''_1 D_S)$

(c) assume a linear relationship between the unknown small end diameter and d.b.h., which effectively replaces $D_S$ with $D$: $(H + b'_0 + b'_1 D)$

(d) substitute corrected H for H in the combined-variable equation:

$$V = b_0 + b_1 D^2 (H + b'_0 + b'_1 D)$$

which expands to:

$$V = b_0 + b_1 D^2 H + b_2 D^2 + b_3 D^3$$

Simpler versions of this hypothesis ($c = b''_1 D_S$ or $c = b''_0$) lead to:

$$V = b_0 + b_1 D^2 H + b_2 D^3$$

$$\text{or} \quad V = b_0 + b_1 D^2 H + b_2 D^2$$

respectively.

The preliminary models were tested and the statistical assumptions checked on the Northern Territory data, to determine whether the models fitted the data sufficiently well to be suitable for use in covariance analyses. Linear regressions were fitted using Grosenbaugh's (1967) REX program.

## (ii) TESTING THE STATISTICAL ASSUMPTIONS

The same problems occurred with testing the statistical assumptions as with model development and partitioning the data, in that homogeneous data sets were not pre-defined. Departures from the assumptions were also very much interrelated (e.g., weighting to correct for heteroscedasticity affected the tests for normality and serial correlation). However it seemed likely that heterogeneity of variance would represent the most serious violation of the assumptions, and testing was started there.

The regression model used for testing the statistical assumptions was

$$V = b_0 + b_1 D^2 H + b_2 D^3$$

which was found to give a reasonably good fit to the data, as discussed in section (iii).

### (a) General Testing Strategy

At this point it was necessary to decide on a suitable approach to the general question of significance testing with the Northern Territory data. A satisfactory balance between Type I and Type II errors (Sokal and Rohlf, 1969) was particularly important, because in many cases tests of significance would be applied simultaneously to a number of different data sets, and the occurrence of Type I errors correspondingly increased. For example, if twenty tests were to be applied simultaneously with a probability level of 0.05, then as Freese (1964) cautions:

> "It is.....well to remember that one-in-twenty chances do actually occur - about one time out of twenty."

This danger could have been minimised by greatly reducing the probability levels used, but only at the expense of increasing the risk of Type II errors and reducing the sensitivity of the tests. The following general approach was therefore adopted:

(i) select a probability level as close as possible to 1/n, where n is the number of tests being carried out simultaneously;

(ii) after testing, compare the outcomes with an expectation due to chance alone, using a chi-square test.

As an example: if 38 simultaneous tests were carried out, a probability level as close as possible to 1/38 would be selected (e.g., 0.02). If 3 out of the 38 tests gave a significant result at the 0.02 probability level, then this observed proportion would be tested against an expectation of 0.02x38, or 0.76 in 38, using a chi-square test.

This represents an oversimplified treatment of the problem. The probability of Type II errors also depends on the nature of the alternative hypothesis (Sokal and Rohlf, 1969), which in this context would be the proportion of significant outcomes which might be present in the data. However some degree of balance between Type I and Type II errors should be effected by using this approach as a general guide when performing the same test simultaneously on a reasonably large number of data sets.

(b) Homogeneity of Variance

Freese (1964) and Draper and Smith (1966) give examples of the way in which heterogeneous variance can be detected from examination of plotted residuals, where the spread of plotted points changes with changes in the independent variable. A quantitative test of homogeneous variance, Bartlett's (1937) test, was applied by Frayer (1966) to inventory remeasurement data to which regressions were fitted. Other tests for heterogeneous variance are discussed by Acton (1959), but he considers Bartlett's test the most robust; it is also the only test which can cope with differing numbers of observations. Bartlett's test is conveniently applied in this case by subdividing the data into classes based on the independent variables and testing for homogeneity of variance across the classes.

As discussed below, results reported in the literature indicated that a relationship between variance and $D^2H$ was likely. Each data set was sorted into ascending order of

$D^2H$ and divided into 10 classes of equal interval; where at least 4 classes contained a minimum of 3 observations Bartlett's test was performed.

A total of 31 out of the 33 data sets fulfilled the above criteria for the application of Bartlett's test. In accordance with the general testing strategy discussed earlier, a probability level of 0.05 was used in testing for heterogeneous variance and the outcomes for all 31 data sets tested for departure from an expectation due to chance alone. Results were:

| | significant | not significant |
|---|---|---|
| observed | 30 | 1 |
| expected (p=0.05) | 1.55 | 29.45 |

corrected chi-square = 511.72 *

The results showed that heteroscedasticity was present in the data and that some form of correction was desirable.

Correcting heteroscedasticity by using logarithmic or similar transformations of the dependent variable is not completely satisfactory. As noted by Chapman and Meyer (1949) and others, a systematic bias occurs in the least squares solution of regressions such as Schumacher and Hall's (1933) logarithmic model, arising from the fact that the mean of the transformed values is consistently too low. Use of weighting rather than transformations to correct heterogeneous variance avoids this type of bias.

Weighting functions used for volume regressions have commonly been developed as functions of $D^2H$. The simple relationship:

$$s^2 = k(D^2H)^2$$

was used by Munro (1964), Sandrasegaran (1969, 1970, 1972), Burley <u>et al</u>. (1972), Allen <u>et al</u>. (1974) and others. Turner (1972) added a constant term to the relationship, and Moser and Beers (1969) used an exponential relationship between $s^2$ and $D^2H$. Gerrard (1966) used a relationship of the form:

$$\ln s = b_0 + b_1 D + b_2 H$$

after finding that $s^2$ was not linearly related to $(D^2H)^2$ for his data; however his "contours of variance" across diameter-height cells represent good approximations to $D^2H$ contours, implying that a linear relationship with $D^2H$ rather than $(D^2H)^2$ might have been satisfactory in his case. Gibson and Webb (1968) used a polynomial in measured tree volume, but found that weights proportional to $1/(D^2H)^2$ gave equally good results.

In view of these findings, the overall relationship between $s^2$ and $D^2H$ was briefly investigated for the Northern Territory data. Because of the different methods of data collection used, the old style and new style data were dealt with separately. Variances within $D^2H$ classes were calculated and plotted against mean $D^2H$ for each class, but the results were somewhat inconclusive, with apparently different trends for the old and new style data. It was also likely that divergent trends of volume with $D^2H$ for different species and localities were inflating the class variances and obscuring the relationship between variance and $D^2H$.

A single weighting function was required to simplify the covariance analyses. Before final groupings had been determined there was no obvious basis for choosing a single data set on which to develop a weighting function. The simple relationships:

$$s^2 = kD^2H$$

$$\text{and} \quad s^2 = k(D^2H)^2$$

were therefore tested for their overall effects on heteroscedasticity. Bartlett's test was repeated on the 31 data sets used earlier, with assumed weights of $1/D^2H$ and $1/(D^2H)^2$ i.e., with deviates transformed by $1/D\sqrt{H}$ and $1/D^2H$ respectively. A probability level of 0.05 was again applied and the outcomes tested for departure from expectation in each case. Results were:

| | significant | not significant | chi-square |
|---|---|---|---|
| trans. by $1/D\sqrt{H}$ | 22 | 9 | 256.91 * |
| trans. by $1/D^2H$ | 1 | 30 | 0.21 NS |
| expected (p=0.05) | 1.55 | 29.45 | |

These results showed that weighting by $1/(D^2H)^2$ rather than $1/D^2H$ was required to reduce heteroscedasticity to non-significant levels. Weighting by $1/(D^2H)^2$ was therefore used for the covariance analyses.

Results of testing for heteroscedasticity with the above weight are given in Table 7.1.

Table 7.1
Results of testing for heteroscedasticity, serial correlation and normality with the model $V = b_0 + b_1 D^2 H + b_2 D^3$.

Key: NS not significant; -- no result (see p. 82);
* significant;
(+) significant positive; (-) significant negative.

| Locality | Species | No. Obs. | Heteroscedasticity | Serial correlation | Normality: Skewness | Normality: Kurtosis |
|---|---|---|---|---|---|---|
| Old style data | | | | | | |
| 02 | 01 | 150 | * | NS | NS | (+) |
| | 02 | 108 | -- | * | NS | NS |
| | 03 | 88 | NS | NS | NS | NS |
| 03 | 01 | 95 | NS | NS | NS | NS |
| | 02 | 103 | NS | NS | (+) | (+) |
| | 03 | 72 | NS | NS | NS | NS |
| 07 | 01 | 86 | -- | * | (+) | (+) |
| | 02 | 420 | NS | * | (-) | (+) |
| 070 | 01 | 42 | NS | * | NS | NS |
| | 02 | 157 | NS | NS | NS | NS |
| New style data | | | | | | |
| 011 | 01 | 65 | NS | * | NS | NS |
| | 02 | 96 | NS | * | NS | NS |
| | 68 | 108 | NS | NS | NS | NS |
| 02 | 01 | 57 | NS | * | (-) | (+) |
| | 02 | 45 | NS | * | NS | NS |
| | 03 | 54 | NS | NS | NS | NS |
| 0211 | 01 | 54 | NS | NS | (-) | (+) |
| | 02 | 54 | NS | NS | NS | NS |
| | 03 | 54 | NS | * | NS | (+) |
| 022 | 01 | 44 | NS | NS | NS | NS |
| | 02 | 44 | NS | * | NS | NS |
| | 03 | 44 | NS | NS | NS | NS |
| | 06 | 44 | NS | NS | NS | NS |
| 031 | 01 | 121 | NS | * | (+) | NS |
| | 02 | 111 | NS | * | NS | NS |
| | 03 | 126 | NS | * | NS | NS |
| | 68 | 131 | NS | * | NS | NS |
| 07 | 01 | 80 | NS | * | NS | NS |
| | 02 | 168 | NS | * | (-) | (+) |
| 091 | 01 | 157 | NS | * | NS | NS |
| | 02 | 156 | NS | * | NS | (+) |
| | 06 | 156 | NS | NS | NS | NS |
| | 68 | 153 | NS | * | NS | NS |

(c) Serial Correlation

Durbin and Watson (1950, 1951) describe a test for first-order serial correlation based on the Von Neumann ratio, and give tables of the significance points of their "d" statistic, which specify upper and lower bounds rather than precise values. Theil and Nagar (1961) have noted the danger of false inference from these tables, in that "no inference possible" - when the statistic falls between the upper and lower bounds - may be interpreted as an absence of evidence for serial correlation; they use a different approximation to specify precise values which are very close to the upper bounds in the Durbin-Watson tables. Hume (1971) considers these and other approximate methods unsatisfactory, and gives methods of calculating the exact probability of obtaining a given value of the Durbin-Watson statistic for a given regression model and number of observations, but only at the expense of considerable computational effort.

It was decided to use the d-statistic but to avoid calculating exact probabilities, because of the excessive amount of computer time required to cover all of the data sets with each of a number of different regression models. In view of the results reported by Koerts and Abrahamse (1968) on the failure of the Durbin-Watson procedure to reject the null hypothesis as often as it should, the modification proposed by Theil (1971) to use the upper bound in Durbin and Watson's (1951) tables as the critical value was adopted. Beyond the upper limit of the tables (100 table; where there is no prior knowledge of the sign of the serial correlation, two-sided tests may be made by combining single-tail tests. It was expected that any serial correlation caused by factors such as those discussed above would probably be positive, and this was confirmed by initial trials.

One-tailed tests for positive serial correlation were applied. Results are given in Table 7.1. The presence of significant serial correlation in more than 50% of the data sets had to be allowed for during the covariance analyses, as discussed later.

(d) Normality

Shapiro et al. (1968) tested nine different procedures for evaluating normality in a comprehensive empirical sampling study with many different probability distributions. They found the W statistic (Shapiro and Wilk, 1965) to provide "... a generally superior omnibus measure of non-normality", but also found that a combination of the standard third and fourth moment tests was the next most powerful out of all the tests considered. Third moment ($\sqrt{b_1}$ or $g_1$) and fourth moment ($b_2$ or $g_2$) tests are described by Snedecor and Cochran (1967) and Sokal and Rohlf (1969).

The W test involves lengthy calculation using large numbers of tabulated coefficients, varying from 1 coefficient for n=2 up to 25 coefficients for n=50; the published table

(Shapiro and Wilk, 1965) also stops at n=50, and evaluation of coefficients for larger values of n is non-trivial. Although the W test is generally more powerful than the third and fourth moment tests the additional effort involved in applying it did not seem to be justified. Combined third and fourth moment ($g_1$ and $g_2$) tests were therefore adopted.

Snedecor and Cochran (1967) describe the use of $g_1$ in testing for skewness and $g_2$ for testing for kurtosis, but they note that no tables of the significance levels of $g_2$ are available for sample sizes less than 200; for smaller sample sizes they suggest an alternative test developed by Geary (1936). Sokal and Rohlf (1969) give corrected formulae for $g_1$ and $g_2$ to allow for smaller sample sizes, and specify that the t-test for the significance of these statistics has infinite degrees of freedom for samples from normal populations.

Values of $g_1$ and $g_2$ were calculated from deviates about fitted regressions with formulae given both by Snedecor and Cochran (1967) and Sokal and Rohlf (1969), together with values of t in the latter case. Trials on a number of data sets indicated that both tests gave similar results for both skewness and kurtosis, even for relatively small numbers of observations. The Sokal and Rohlf statistic was used in most cases for convenience, and both methods were used in borderline cases. Results are given in Table 7.1.

In view of the comments by Sokal and Rohlf (1969) noted earlier (page 72) on the consequences of moderate non-normality, the observed departures from normality were considered to be insufficiently serious to invalidate the covariance analyses.

### (iii) TESTING THE PRELIMINARY MODELS

#### (a) Indices of Fit

After a regression equation has been fitted by least squares, some method of judging goodness of fit must be used, assuming that the regression has been shown to be significant by a standard F-test (e.g., Freese, 1964). The normal indices of fit such as standard error of estimate ($s^2_{\bar{x}}$) and coefficient of determination ($R^2$) are described by Draper and Smith (1966) and others, and have been widely used for testing and comparing volume regressions. However these indices are only comparable between regressions with the same dependent variable; if transformations such as log V or $V/D^2H$ are used then transformed and untransformed equations can no longer be directly compared. Furnival (1961) solved this problem with an index based on maximum likelihood for comparing such regressions. His index has been used by Shield (1965), Sandrasegaran (1969, 1970, 1972), Burley et al. (1972) and others.

Draper and Smith (1966) caution against the uncritical use of $R^2$ or standard error of estimate in judging goodness of fit, because of the false improvement produced by adding a large number of parameters to the model, especially with a relatively small number of observations. Ezekiel and Fox (1959) and Snedecor and Cochran (1967) show how the estimate of $R^2$ can be adjusted for both number of parameters and number of observations.

Good results for these goodness of fit criteria do not ensure that the chosen regression model is satisfactory. If the postulated model is incorrect then the least squares estimates of the coefficients are biased (Draper and Smith, 1966; Wonnacott and Wonnacott, 1970) and the deviates may show the type of bias mentioned previously in the discussions of serial correlation. For example, Cromer (1959) found that multiple regressions applied to Araucaria data from Papua New Guinea had high $R^2$ values and low standard errors of estimate, but did not show satisfactory fits over the whole range of the data.

Draper and Smith (1966) also discuss a test of lack of fit based on a comparison of "pure error" variance and the observed error variance about the model; the estimate of pure error can be obtained only if repeat observations of Y for the same values of X are available. Gerrard (1966) used this approach for testing goodness of fit by partitioning the sum of squares into diameter-height cells and using the within-cell variances to obtain an estimate of pure error.

Various other indices have been used. Beers and Gingrich (1958) used both standard error of estimate and the standard errors of the regression coefficients for comparison of alternative equations. Simpfendorfer (1959) used correlation coefficient, coefficient of variation and percentage confidence limits of mean predicted volume for various sample sizes. Grosenbaugh (1967) used residual mean square (the square of the standard error of estimate) as the criterion of best fit in the combinatorial screening option of his REX program. Gibson and Webb (1968) had the problem of comparing partitioned (overlapping) regressions with single weighted and unweighted regressions, and used variances of deviates within 10 different volume classes as a basis of comparison; these comparisons were carried out on an independent set of test data rather than on the data used for fitting the regressions.

The use of separate test data is desirable, in that it provides an independent check on model performance and some degree of assurance that the relationship developed is generalisable beyond beyond the data to which it was fitted. Unwin and Bowling (1951) reserved one third of each set of data as test data and used the remainder for fitting the model; Gibson and Webb (1968) used similar proportions for fitting and testing. The many locality/species combinations made the use of test data impractical in this study. Turner (1972) simulated test data by weighting diameter classes in the compilation data with their frequency distributions as determined by forest inventory, but this would obviously not provide a completely independent test of model performance.

In the absence of test data, some criteria based on goodness of fit to the compilation data had to be used for testing the models. Gerrard's (1966) method of partitioning the data or Gibson and Webb's (1968) volume classes were not possible with the smaller data sets in the present study, which left only general tests of overall goodness of fit. These are discussed in the next section.

(b) Testing the Models

The main model to be tested was that proposed earlier in section (ii)(b), i.e.:

$$V = b_0 + b_1 D^2H + b_2 D^2 + b_3 D^3$$

or some simpler version of it. The basic combined-variable model

$$V = b_0 + b_1 D^2H$$

was also tested concurrently, to ensure that this model was a valid starting point for model development.

Because of the tentative assumptions used in developing the preliminary model it was necessary to first investigate the form of the model more closely before using it in any analyses. A rapid empirical method of testing was available in the combinatorial screening option included in the REX program. Although combinatorial screening - or any automatic selection procedure - was not considered appropriate for logical model development, it provided a convenient method of validating the postulated preliminary model, without necessarily influencing the development of final models. Combinatorial screening was carried out on a subsample of the data, which was selected as a restricted subsample of 9 data sets from 9 different localities, with each data set a subsample selected randomly by species. An upper limit of three variables per model was applied, both because of the number of variables in the postulated model and because of trials which indicated that "overfitting" (Draper and Smith, 1966) occurred with more than about three or four independent variables.

Combinatorial screening was carried out on each of the 9 data sets in the subsample. To judge the performance of the proposed model - or some simpler version of it - the 10 best regressions for each data set were examined. Results were that $D^2H$ was the most common variable with 30 occurrences, $D^3$ was the second most common term with 23 occurrences, and $D^2$ was the fifth most common with 14 occurrences. Observed occurrences of the models were:

$V = b_0 + b_1 D^2H + b_2 D^3$: 4 occurrences (most common)

$V = b_0 + b_1 D^2H + b_2 D^2$: 3 occurrences (one of several)

$V = b_0 + b_1 D^2H + b_2 D^2 + b_3 D^3$: 1 occurrence

The 10 best rankings confirmed the expectation that the linear regression of best fit would vary considerably between data sets. However it was highly desirable to select a common model for all data sets, so as to simplify the covariance analyses and allow for comparisons on a common basis among all of the data. The frequency of occurrence of the variables $D^2H$ and $D^3$, together with the most common occurrence of the model including these variables, made it likely that this model would provide the best compromise for all data sets. The model:

$$V = b_0 + b_1 D^2 H + b_2 D^3$$

was therefore selected for further testing and the other two alternatives were dropped.

Goodness of fit was investigated both for the combined-variable model and the above model on each species within each locality. Fit was determined initially from the adjusted $R^2$ value, and from an examination of plotted residuals to detect any evidence of serious departures from each model; testing the regressions for significance was found to be unnecessary in the light of the high $R^2$ values obtained. The models were fitted with the weighting function $1/(D^2H)^2$, and an equivalent transformation (i.e., $1/D^2H$) was applied to plotted residuals. The $R^2$ values were adjusted as follows (Yamane, 1967; Snedecor and Cochran, 1967):

$$\text{adjusted } R^2 = 1 - ((1-R^2)(n-1)/(n-k-1))$$

where n is the number of observations and k the number of independent variables in the model.

Results are given in Table 7.2. The adjusted $R^2$ values for the combined-variable model ranged from 0.874 to 0.975, and ranged from 0.905 to 0.981 for the second model.

Addition of the $D^3$ term was also tested for significance with a standard F-test (Freese, 1967) at the 5% level; results are given in Table 7.2. The addition of $D^3$ was not significant in 6 cases out of 33 and, in accordance with the testing strategy discussed earlier (page 79) for simultaneous tests, this observed frequency was compared with

Table 7.2

Goodness of fit of preliminary linear models.

| Locality | Species | No. Obs. | $V=b_0+b_1D^2H$ Adjusted $R^2$ | $V=b_0+b_1D^2H+b_2D^3$ Adjusted $R^2$ | Addition of $D^3$ |
|---|---|---|---|---|---|
| Old style data | | | | | |
| 02 | 01 | 150 | .919 | .923 | * |
| | 02 | 108 | .901 | .929 | * |
| | 03 | 88 | .906 | .925 | * |
| 03 | 01 | 95 | .946 | .948 | * |
| | 02 | 103 | .874 | .905 | * |
| | 03 | 72 | .902 | .927 | * |
| 07 | 01 | 86 | .933 | .935 | * |
| | 02 | 420 | .932 | .942 | * |
| 070 | 01 | 42 | .908 | .912 | NS |
| | 02 | 157 | .958 | .960 | * |
| New style data | | | | | |
| 011 | 01 | 65 | .926 | .925 | NS |
| | 02 | 96 | .965 | .970 | * |
| | 68 | 108 | .941 | .940 | NS |
| 02 | 01 | 57 | .931 | .939 | * |
| | 02 | 45 | .922 | .932 | * |
| | 03 | 54 | .942 | .956 | * |
| 0211 | 01 | 54 | .919 | .923 | NS |
| | 02 | 54 | .935 | .954 | * |
| | 03 | 54 | .930 | .942 | * |
| 022 | 01 | 44 | .959 | .961 | NS |
| | 02 | 44 | .975 | .981 | * |
| | 03 | 44 | .965 | .972 | * |
| | 06 | 44 | .956 | .964 | * |
| 031 | 01 | 121 | .948 | .953 | * |
| | 02 | 111 | .962 | .975 | * |
| | 03 | 126 | .955 | .965 | * |
| | 68 | 131 | .948 | .949 | NS |
| 07 | 01 | 80 | .953 | .961 | * |
| | 02 | 168 | .954 | .961 | * |
| 091 | 01 | 157 | .965 | .975 | * |
| | 02 | 156 | .966 | .977 | * |
| | 06 | 156 | .962 | .970 | * |
| | 68 | 153 | .954 | .955 | * |

an expectation of 1.65 in 33 due to chance alone (for $p = 0.05$). There was found to be a significant departure from expectation, indicating that the addition of $D^3$ did not always produce a significant improvement in fit.

Plots of the transformed residuals showed overall fits which ranged from good to fair. When compared with the combined-variable model, the addition of $D^3$ appeared to improve the fit for smaller trees while at the same time introducing some apparent bias among the very largest sizes. In general, however, the $D^3$ model showed a reasonably good fit among the tree sizes represented by the bulk of the data.

The model was accepted as adequate for testing for differences within the data. Further model development was carried out after final data groupings had been determined.

### (iv) GROUPING THE DATA

Earlier discussion in Chapter 3 has covered the ways in which different workers dealt with variation between species and localities, but quantitative testing of the significance of this variation is reported less commonly. Golding and Hall (1961) fitted the combined-variable model to three Canadian species and tested the regression coefficients for significant differences. Burley _et al_. (1972) used the Australian equation with _Pinus caribaea_ from Cuba, and tested the regressions fitted to three different altitude classes for differences by covariance analysis. Barnard _et al_.

(1973) used data from the northeastern United States, and tested Girard form-class measurements for significant differences within species due to location. Nash (1973b) refers to taper regressions fitted to different species and diameter classes for rain forest data from Surinam, which were tested for significant differences, but gives no details of the results. Apart from these examples, little seems to have been done by way of objective testing. Comparison of scatter diagrams was used by Hindley (1973) for the rapid comparison of large numbers of volume regressions for rain forest species in Sarawak, but the comparisons were essentially subjective.

The present study provided an opportunity to develop an objective testing procedure for data covering a range of localities and species, and so produce homogeneous groups of data.

FAO (1973) suggest several methods of testing for differences among data sets: (i) by comparison of scatter diagrams; (ii) by covariance analysis; and (iii) by multivariate analysis. Covariance analysis is described in standard textbooks such as Snedecor and Cochran (1967), and its application to forestry data is described by Freese (1964), Kozak (1970) and Cunia (1973). It allows the objective comparison of two or more regression equations which have been fitted to different samples, to determine whether the samples could have come from the same population. As with an ordinary analysis of variance, associated _a priori_ or _a_

<u>posteriori</u> tests may be used for testing differences between individual samples in the case when more than two samples are included in the analysis.

Because of the very large number of potential comparisons within and between the species and localities represented in the data, it was necessary to develop a planned approach, both to produce logical groupings and to keep the number of comparisons down to manageable levels. The approach used was as follows:

(i) combine contiguous localities into regions;

(ii) test for locality differences within each species within a region;

(iii) if a species showed no differences between localities within more than one region, test for differences between regions.

The regional groupings used were:

Old style data

Region 1

| | |
|---|---|
| Melville and Bathurst Islands | 02 |
| Garden Point | 03 |

Region 2

| | |
|---|---|
| Gove | 07 |
| Gove (single trees) | 070 |

New style data

Region 1

| | |
|---|---|
| Melville and Bathurst Islands | 02 |
| Melville Island West - Garden Point | 0211 |
| Melville Island East | 022 |

Region 2

| | |
|---|---|
| Lake Evella | 011 |
| Gove | 07 |

Region 3

| | |
|---|---|
| Murgenella | 031 |
| Maningrida | 091 |

The covariance analyses were carried out using the model

$$V = b_0 + b_1 D^2H + b_2 D^3$$

weighted by $1/(D^2H)^2$. The method of dummy variables (Freese, 1964; Grosenbaugh, 1967) was used with the REX program. In cases where significant differences were detected during comparisons of these localities (region 1, new style data), additional comparisons were carried out (Cunia, 1973) to determine if any two localities could be combined. Although such _a posteriori_ comparisons normally require appropriate adjustments to the probability levels (Acton, 1959), such adjustments were unnecessary here because all possible combinations of pairs (i.e., three) were tested.

Old and new style data were again tested separately. Probability levels of 0.05 for the F-tests were selected as before, based on the probable number of tests to be carried out.

The levels of serial correlation detected in the data were of considerable relevance to the covariance analyses, in that the apparent degrees of freedom for the F-tests would have been reduced by unknown amounts. Results of F-tests involving data sets with significant serial correlation were therefore examined with this problem in mind. However it was found that, even when quite large arbitrary reductions were made in the assumed degrees of freedom (e.g., more than half) to allow for the possible effects of serial correlation, the outcomes were not altered. It was obvious from the relatively small changes in the critical values of F produced in this way that the effects of serial correlation would become important only in borderline cases, and that the results of covariance analyses would generally be quite robust with respect to serial correlation.

The final groupings produced are shown in Table 8.1, page 117. Only five groupings of localities proved to be possible, with two for the old style data and three for the new style data; the remaining 19 data sets each covered only one locality for a given species. The data for locality 070 (Gove, single trees, old style) were found to be incompatible with data for locality 07 (Gove, old style) collected from plots within the same area; only the 07 data were used, because they had been collected by objective sampling methods.

(v) FURTHER MODEL DEVELOPMENT

With data groupings determined it became possible to begin developing final models. For this purpose the single largest data set was selected, i.e., localities 02, 03, and 07 (old style data), species 02. This data set had several advantages: it was by far the largest with 631 observations; it combined data from widely separated localities (Melville-Bathurst and Gove) and was therefore presumably somewhat more representative than data from a single locality; and in addition the data had been collected under the older statistically valid method of objective subsampling.

The first matter requiring investigation was the adequacy of the weighting function $1/(D^2H)^2$, which had been developed earlier by a somewhat unsatisfactory method of trial and error because of the large number of data sets involved. The data were divided into $D^2H$ classes of equal interval, the $D^3$ model was fitted with the above weighting function and the variance of the residuals calculated within each $D^2H$ class. Results are given in Table 7.3.

A plot of the results indicated that variance was approximately linear with (mean $D^2H)^2$. A model of the form

$$s^2 = b_0 + b_1 D^2H + b_2(D^2H)^2$$

was fitted to the class results, weighted by the number of observations in each class, and it was found that addition of the $D^2H$ term was not significant. Further testing with a model of the form

Table 7.3

Variance about the model $V = b_o + b_1 D^2H + b_2 D^3$ (weighted by $1/(D^2H)^2$) fitted to old style data from localities 02, 03 and 07, species 02.

| $D^2H$ class | Mean $D^2H$ | Number of observations | Variance of residuals |
|---|---|---|---|
| 0 - 2500 | 1362.8 | 179 | 0.000121 |
| 2500 - 5000 | 3652.9 | 181 | 0.000545 |
| 5000 - 7500 | 6141.8 | 98 | 0.002063 |
| 7500 - 10000 | 8709.2 | 68 | 0.005083 |
| 10000 - 12500 | 11265.4 | 29 | 0.003225 |
| 12500 - 15000 | 13560.3 | 24 | 0.006720 |
| 15000 - 17500 | 16291.7 | 19 | 0.018086 |
| 17500 - 20000 | 18400.8 | 9 | 0.038284 |
| 20000 - 22500 | 21154.1 | 10 | 0.018451 |
| 22500 - 25000 | 23023.5 | 5 | 0.037599 |
| 25000 + | 39162.2 | 9 | 0.117616 |

---

$$s^2 = b_o + b_1 (D^2H)^2$$

showed the constant term to be non-significant. This indicated a relationship of the form

$$s^2 = k(D^2H)^2$$

and confirmed the adequacy of $1/(D^2H)^2$ as a weighting function.

The volume model itself was then examined. The $D^3$ model had already been shown to perform reasonably well, and therefore the original model postulated in section (ii)(b)

$$V = b_o + b_1 D^2H + b_2 D^2 + b_3 D^3$$

was tested. Addition of the $D^2$ term proved to be non-significant. This made it necessary to re-examine what was required in terms of model performance.

Assuming no major changes in form, the volume of the merchantable bole of a hardwood tree would vary with $D^2$ if log length remained constant, and would vary with $D^3$ if log length was strictly proportional to diameter. As indicated by the stand tables in Appendix 2, log length for the Northern Territory data generally showed a weak positive correlation with diameter, which would tend to produce a linear relationship between V and D to some intermediate power, probably much closer to 2 than to 3. The behaviour of form and taper with changes in diameter and log length appeared to be extremely erratic, which made it virtually impossible to determine to what extent it would tend to affect this highly oversimplified assumption.

The expected behaviour of volume with changes in log length was conditioned by the truncation of the merchantable bole at crown break or some other limiting point. This produced a wide range of log lengths for all diameters, and with generally positive taper the shorter logs tended to have markedly larger small end diameters than the larger log lengths, which in turn affected the rate of increase in volume with increasing log length. The expectation therefore was that the rate of increase in volume with log length would be reduced as log length increased, i.e., that V would show a linear relationship with H to some power less than 1.

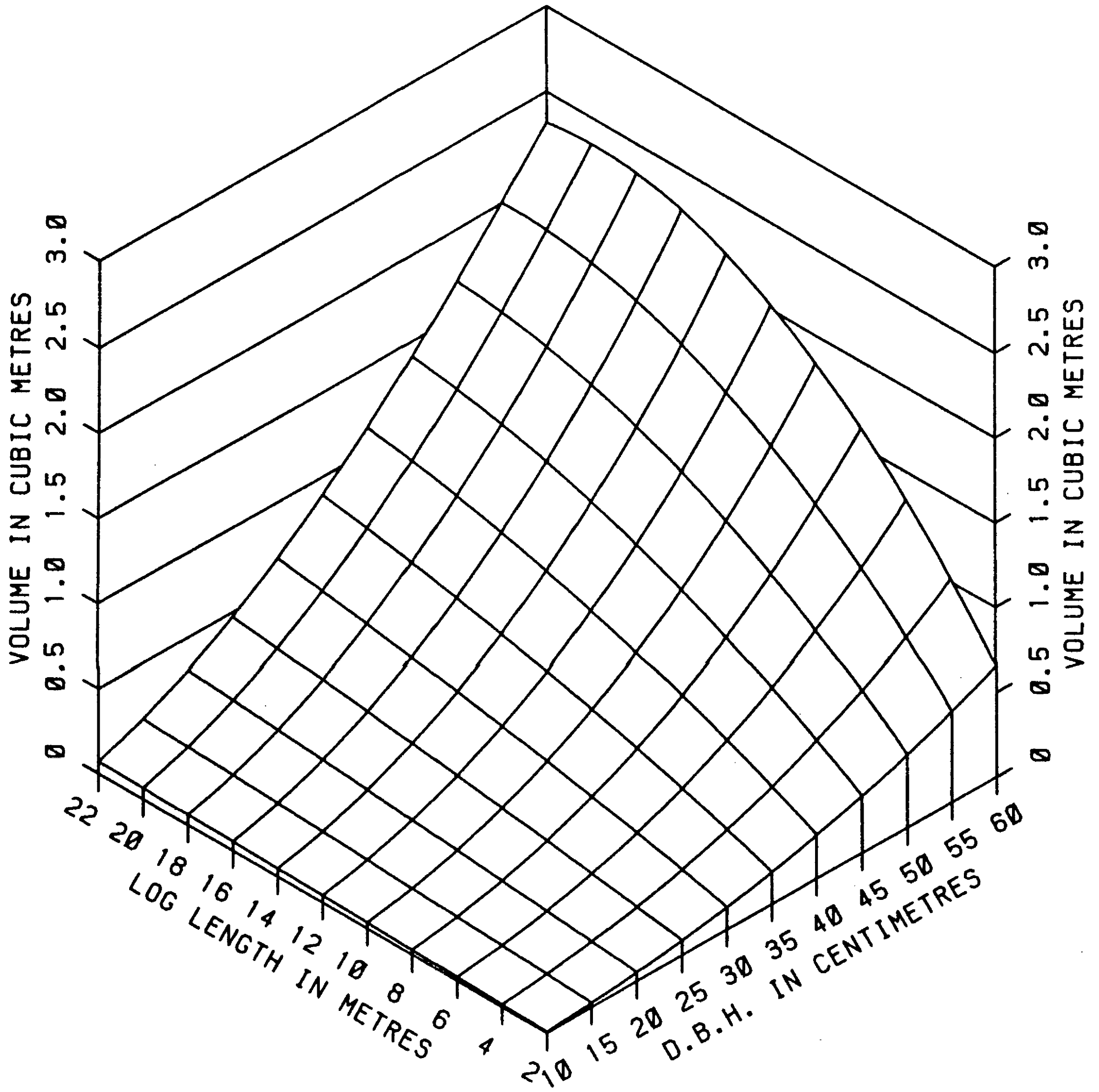
The minimum linear model which could be expected to reflect the required type of behaviour is:

$$V = (b_0 + b_1 D + b_2 D^2)(b_3 + b_4 H - b_5 H^2)$$

Figure 7.1

Behaviour of the linear model

$$V = (b_0 + b_1D + b_2D^2)(b_3 + b_4H - b_5H^2)$$



with signs of coefficients as shown. This model expands to a total of eight independent variables and obviously involves considerable "overfitting"; however it was tested to determine whether it would behave as required. Figure 7.1 shows the behaviour of this model.

Not unexpectedly, the behaviour of the model was illogical, especially when extrapolated beyond the upper limits of the data. The negative quadratic in H can be seen in the figure to reach a maximum and then begin declining; in this instance the maximum occurs beyond the upper limit of the data, but there is no reason why this should always be so.

It appeared as if the linear models tested so far may have represented somewhat unsatisfactory approximations to a non-linear relationship. In accordance with the comment by Draper and Smith (1966) quoted earlier (page 73), non-linear models were considered as the next stage of model development.

# CHAPTER 8 : NON-LINEAR REGRESSION MODELS

Non-linear regressions have been used infrequently as tree volume models, and there appear to be no reports in the literature of their use with tropical hardwoods. The large amount of data available for the Northern Territory provided a good opportunity for testing the performance of non-linear models over a range of species and localities.

## (i) FITTING NON-LINEAR MODELS

Parameter estimates for intrinsically non-linear regressions must be obtained by an iterative process of successive approximations, starting with initial estimates and converging to a final result. Various methods are discussed by Williams (1959), Draper and Smith (1966) and Snedecor and Cochran (1967). A concise overview is provided by Bard (1967), who discusses two main methods under the heading of the Gauss-Newton method and the Davidon-Fletcher-Powell method. All methods attempt to minimise the residual sum of squares, or usually to maximise the objective function

$$-\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$$

Generally, no single method can be assumed satisfactory for all cases; as Draper and Smith (1966) state: "In general,... given a particular method, a problem can usually be constructed to defeat it."

Bard (1967) recommends the Gauss-Newton method for straightforward parameter estimation, particularly when the fit of the model to the data is expected to be reasonably good. The trials with linear models described in the previous chapter indicated that a good fit was highly likely with non-linear models, and therefore the Gauss-Newton method was favoured.

Marquardt (1963) and Draper and Smith (1966) have observed that the Gauss-Newton method may not always converge satisfactorily. Bard's (1967) Nonlinear Parameter Estimation and Programming (NLPE) program incorporates a number of refinements, including the optional use of constraints on the parameters and changes to the Hessian matrix to make it always positive definite. However as noted above, there was no certainty that one particular method would be successful, and it was considered desirable to have a second method in reserve. Bard's (1967) NLPE program provided both the Gauss-Newton and Davidon-Fletcher-Powell method as options, and it was therefore used for fitting non-linear models to the Northern Territory data.

(ii) MODEL DEVELOPMENT

As foreshadowed in the previous chapter, a model was required which would incorporate D to a power somewhat greater than 2 and H to a power less than 1. A model of this type was originally proposed by Schumacher and Hall (1933), who reasoned that a correlation of form factor with D and H would change their powers from 2 and 1 respectively; they used a logarithmic transformation of their basic equation

$$V = b_0 D^{b_1} H^{b_2}$$

to produce the logarithmic tree volume equation. Moser and Beers (1969) avoided the bias inherent in the logarithmic transformation by fitting the untransformed model as a non-linear regression and estimating the parameters directly. However they retained the original condition of constraining the regression surface through the origin.

Newnham (1967) proposed a modification to the combined-variable model which involved using parameter estimates obtained by fitting a logarithmic equation as the exponents of D and H, in place of 2 and 1 respectively; the modification provided "... small but consistent improvements in accuracy". This two stage approach was improved upon by Turner (1972) who used the same model:

$$V = b_0 + b_1 D^{b_2} H^{b_3}$$

but estimated the parameters directly by non-linear methods.

The above model was adopted for testing with the Northern Territory data. It appeared to be the simplest non-linear model which would behave as required, without being subject to constraints such as the absence of a constant term.

The data set used previously for testing the preliminary linear model (old style data, localities 02, 03 and 07, species 02) was also used in initial trials with the non-linear model. The model was fitted - initially unweighted - using the Gauss-Newton option in Bard's (1967) NLPE program, with initial estimates of the parameters obtained from the prior fitting of Schumacher and Hall's (1933) logarithmic equation. Convergence was achieved after only 6 iterations, giving the model

$$V = -0.01683 + 0.000084998\ D^{2.0276}\ H^{0.68403}$$

Bartlett's test on the residuals confirmed that significant heteroscedasticity was present, and examination of variances within $D^2H$ classes indicated that $1/(D^2H)^2$ would again be a suitable weighting function. However weighting the model created problems in achieving convergence; although the unweighted model had used only 8 seconds of computer time, the weighted model had still not converged after 10 minutes. Trials on a number of smaller data sets achieved convergence (after more than 14000 iterations in one case), but examination of the residuals indicated that in most cases a minimum had not been reached, despite the fact that a minimum was indicated by the signs of the eigenvalues of the Hessian matrix (Morrison, 1976).

Turner (1972) also had convergence problems with the same non-linear model and a similar weighting function, although Moser and Beers (1969) did achieve convergence with their somewhat simpler model and an an exponential weighting function. Further trials using the Davidon-Fletcher-Powell option and using Moser and Beer's model as an alternative were unsuccessful. Convergence was achieved with the original data set after 346 iterations by changing the weighting function from $1/(D^2H)^2$ to $1/D^2H$, but from earlier results with the linear models it seemed likely that this weighting function would not adequately correct the heteroscedasticity present in the data.

Following suggestions from J.W. Leech (pers. comm.) the deviates were rescaled to correct the very small values produced following transformation by $1/D^2H$. The Gauss-Newton option of NPLE then successfully converged in a reasonable time to give sensible parameter estimates. Trials with a number of data sets indicated that rescaling the deviates by a factor of 1000 generally produced the best balance between the number of iterations, which approached a minimum with a scaling factor approximately equal to mean $D^2H$, and the standard deviations of the parameter estimates, which increased with increases in the scaling factor. The weighted model produced with the original data set and a scaling factor of 1000 was:

$$V = -0.00734 + 0.000061205\ D^{2.1025}\ H^{0.70117}$$

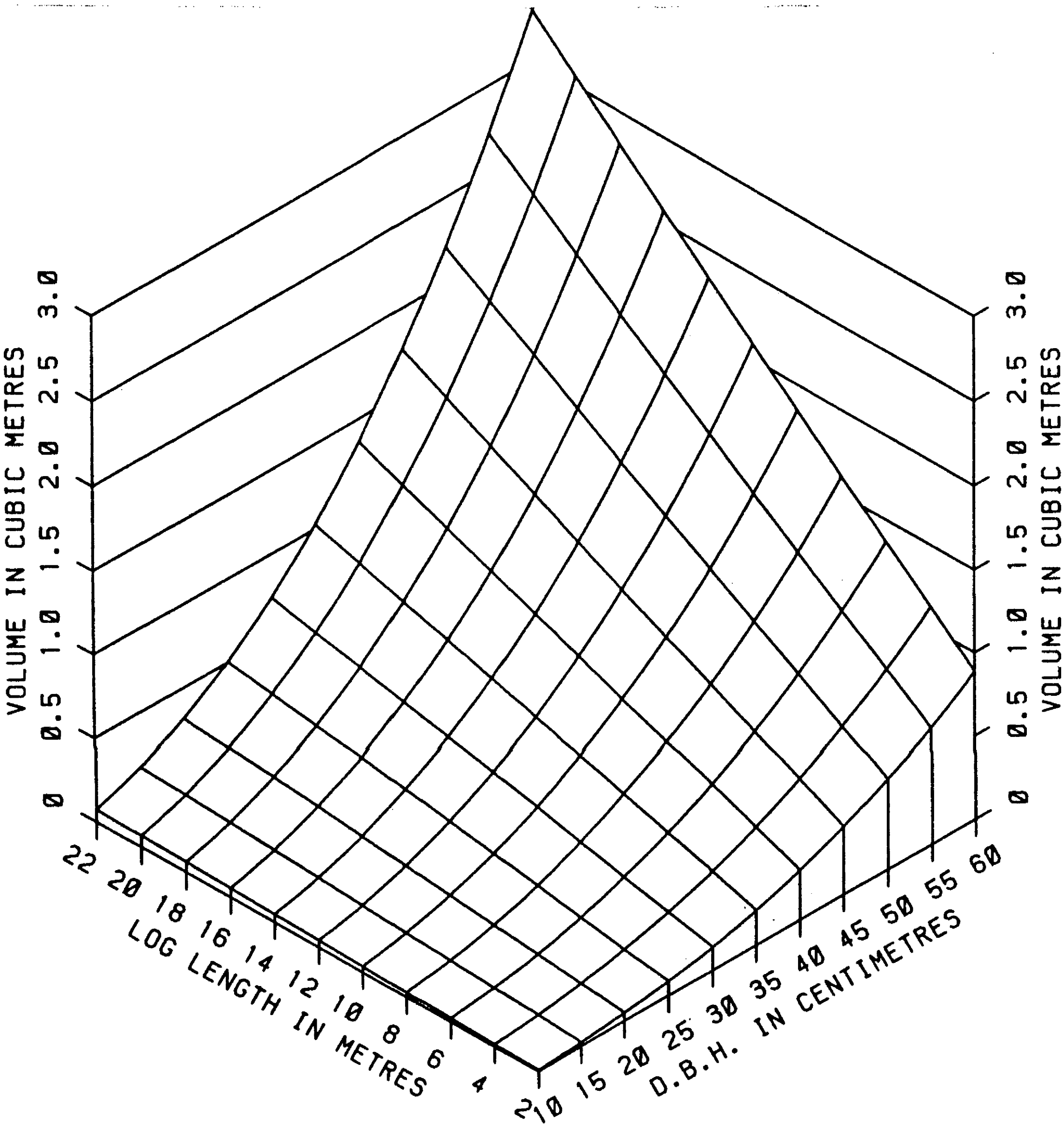
The behaviour of this model is shown in Figure 8.2. It appeared to provide the type of response postulated in the discussion in Chapter 7, and seemed suitable for fitting to the remaining data sets for further testing.

Finally the model was briefly investigated to determine whether there were any grounds for reducing the number of parameters to be estimated. Omission of the constant term as per Moser and Beers (1969) could not be justified, as this term was significantly different from zero (-0.00734 with an s of 0.00067). Nor could a modification suggested by Dwight (reported by Spurr, 1952) to Schumacher

Figure 8.1

Behaviour of the model

$$V = b_0 + b_1 D^2 H + b_2 D^3$$



and Hall's (1933) original equation be justified: the exponents of D and H (2.1025 with s = 0.0034, and 0.70117 with s = 0.00267) obviously gave a total which was significantly different from 3. The above model was therefore adopted for further testing.

## (iii) THE FINAL MODEL

### (a) Comparison of Linear and Non-linear Models

Linear and non-linear models are not commonly compared in the literature. Moser and Beers (1969) used Furnival's (1961) index of fit to compare the logarithmic model with the equivalent non-linear model. Turner (1972) used standard error of estimate (SEE) to compare his non-linear model with several linear models, and also compared model behaviour over the range of his data. Young and Vassiliou (1974) compared a linear and non-linear model by calculating a chi-square value from a comparison of observations with model predictions in each case.

As mentioned in Chapter 6, methods of hypothesis testing for non-linear models are not well developed. Comparisons between linear and non-linear models are therefore to some extent only indicative, with indices such as SEE, for example, only approximate in the non-linear case because of the lack of exact methods for determining degrees of freedom. Likelihood indices such as Furnival's (1961) index may not always behave consistently, as can be seen from Moser and

Beer's (1969) published results, where only minor changes in the coefficients between their weighted and unweighted model produced a very large change in the Furnival Index. The use of chi-square by Young and Vassiliou (1974) represents a measure of the performance of a model as a predictor - independent of model form - and so circumvents the problem to some extent, but is most suited to integer observations of the dependent variable.

For models fitted to the same data set with a relatively large number of observations, the SEE represents only a simple square root transformation of the residual SS in each case, with adjustments for the number of parameters in each model having negligible effect. When a weighting transformation is used which is highly correlated with volume (e.g., $1/D^2H$), then a chi-square index also becomes little more than a simple proxy for the residual SS, in that the denominator in the expression

$$\Sigma(\text{observed} - \text{expected})^2/(\text{expected})$$

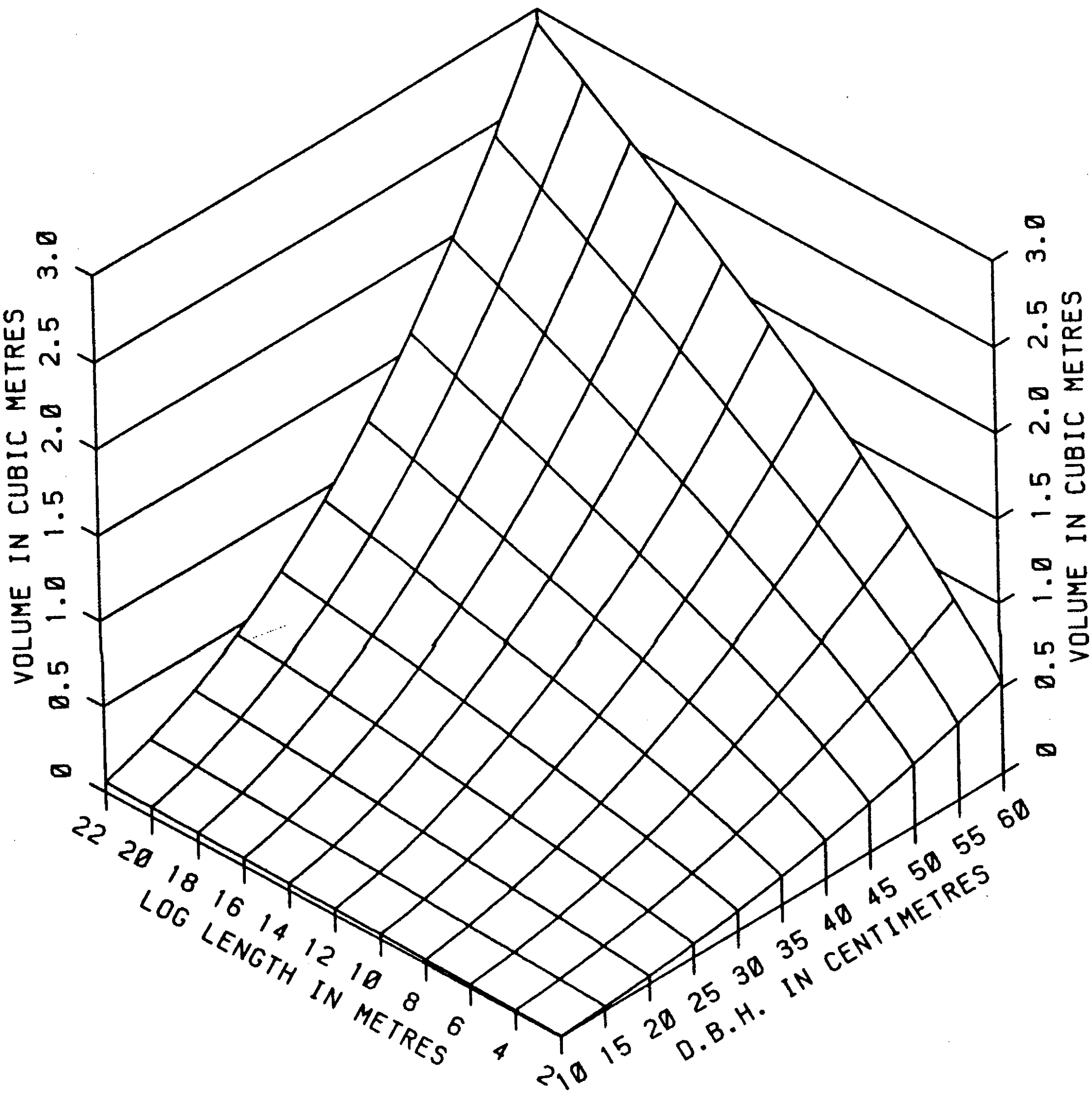
tends towards a constant, i.e., $V/(D^2H)$. For these reasons, and in view of the lack of well-developed techniques for hypothesis testing with non-linear models, comparisons between the linear and non-linear models were confined to residual SS values and general considerations of model behaviour in each case.

Table 8.1 gives the residual SS for both the linear $D^3$ model and the non-linear model on each of the final data groupings. In 17 cases out of 24 the non-linear model

Figure 8.2

Behaviour of the model

$$V = b_0 + b_1 D^{b_2} H^{b_3}$$



produced a better fit to the data. An approximate indication of overall model performance across all of the data was obtained by pooling all of the residual SS values for each model, giving a total of $13.93 \times 10^{-8}$ for the non-linear model and $14.38 \times 10^{-8}$ for the linear model; this confirmed the superior performance of the non-linear model.

Model behavior was then examined, using the same data set as in the previous section. Figures 8.1 and 8.2 depict the behaviour of the linear and non-linear models respectively. The linear model could not provide the kind of curvilinear relationship with height which was required, because it included H only as a linear term, and in addition it gave considerably higher predicted volumes than the non-linear model for larger trees. Comparison of the plotted residuals for each model (Figure 8.3) indicated that among the limited number of larger trees - above about 1 cubic metre - the linear model tended to overestimate volume, while the non-linear model performed satisfactorily. There appeared to be little difference between the two models among the smaller sized trees. The non-linear model was accepted as giving a better fit for larger trees than the linear model, as well as an overall better fit to all of the data. In addition it provided the expected type of behaviour for merchantable bole volume of hardwood trees.

(b) Examining the Non-linear Model

There were no exact methods available for covar-

Table 8.1

Goodness of fit of the linear and non-linear models.

| Locality | Species | No. Obs. | Residual SS ($\times 10^8$) for model: $V=b_0+b_1D^2H+b_2D^3$ | and $V=b_0+b_1D^{b_2}H^{b_3}$ |
|---|---|---|---|---|
| Old style data | | | | |
| 02 | 01 | 150 | .6285 | .6184 |
| 03 | 01 | 95 | .2444 | .2456 |
| 07 | 01 | 86 | .4512 | .4463 |
| 02+03+07 | 02 | 631 | 2.9999 | 3.0633 |
| 02+03 | 03 | 160 | .6320 | .5618 |
| New style data | | | | |
| 011 | 01 | 65 | .4128 | .3324 |
| 02+022 | 01 | 101 | .3870 | .4172 |
| 0211 | 01 | 54 | .1797 | .1743 |
| 031 | 01 | 121 | .6787 | .6008 |
| 07 | 01 | 80 | .2681 | .2761 |
| 091 | 01 | 157 | .4765 | .4620 |
| 011 | 02 | 96 | .2530 | .2237 |
| 02+0211+022 | 02 | 143 | .4512 | .4519 |
| 031 | 02 | 111 | .3366 | .3323 |
| 07 | 02 | 168 | .9025 | .7486 |
| 091 | 02 | 156 | .4178 | .3880 |
| 02+022 | 03 | 98 | .3414 | .3386 |
| 0211 | 03 | 54 | .1609 | .1596 |
| 031 | 03 | 126 | .6540 | .6751 |
| 022 | 06 | 44 | .2047 | .1595 |
| 091 | 06 | 156 | .9048 | .8439 |
| 011 | 68 | 108 | .7237 | .7187 |
| 031 | 68 | 131 | .7032 | .7404 |
| 091 | 68 | 153 | .9714 | .9479 |

iance analyses using non-linear models and, despite the apparent bias in the linear model for larger trees and its somewhat unsatisfactory response with height, the fit of each model was roughly comparable over the bulk of the data. The data groupings produced from the covariance analyses with the linear $D^3$ model were therefore used as final groupings for the nonlinear model as well. Appendix 3 lists the parameter estimates for the non-linear model fitted to each data set.

### Biological Validity

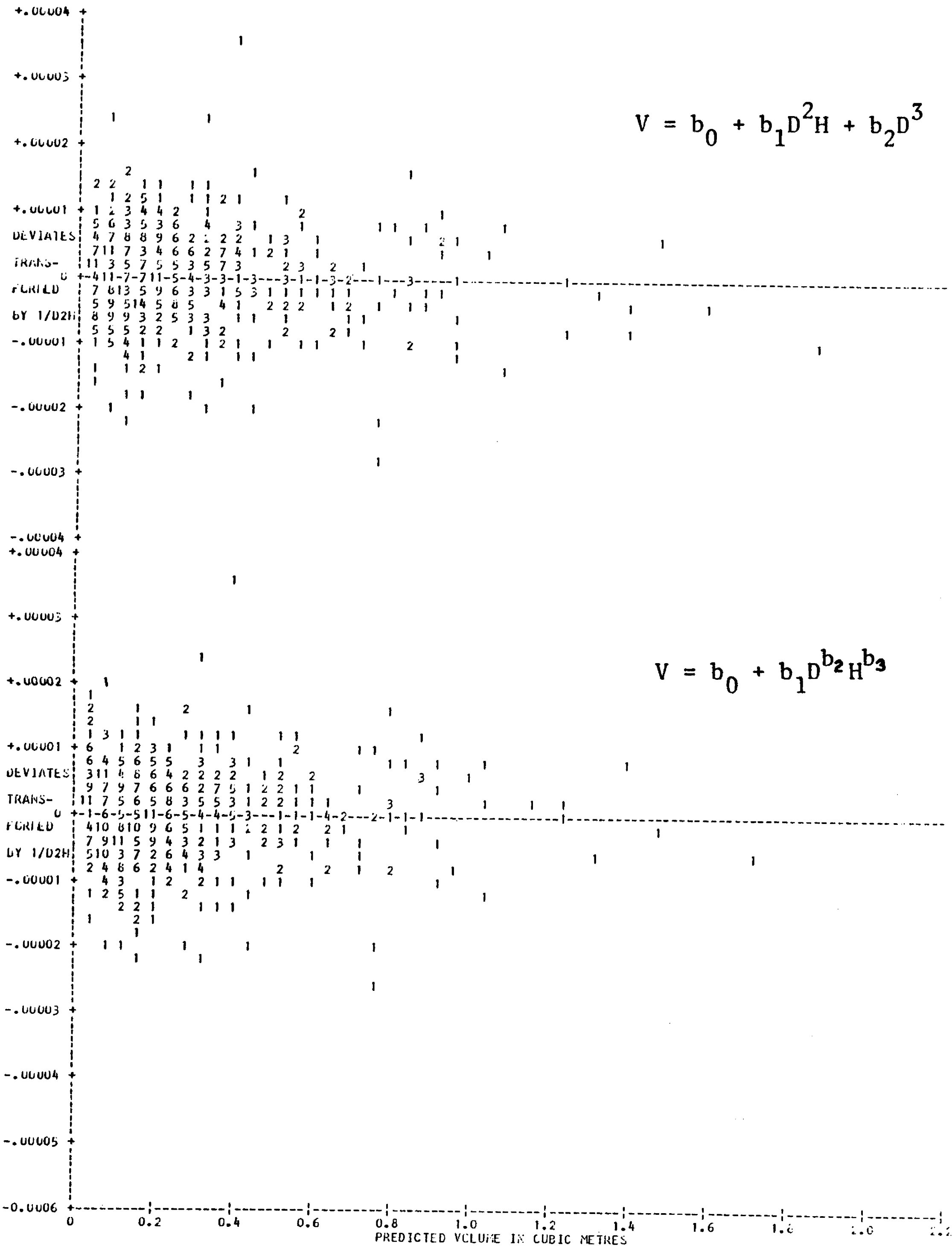
Because of the ease with which a large number of alternative models can be fitted to the same data by using modern computing techniques, consideration must be given to the biological validity of any model which is adopted. Kozak (1973) has discussed situations where conditioned regressions may not faithfully reflect the behaviour of the data, and Schreuder and Swank (1973) rejected a model with apparently good fit because it was not "biologically interpretable". The expected behaviour of merchantable bole volume for hardwood trees has been discussed in Chapter 7. The non-linear models fitted to the final data groupings were examined not only to determine whether they provided this particular type of behaviour, but also to ensure that any other features of model response followed sensible trends.

The values for the exponent of D, i.e., $b_2$ in the model:

$$V = b_0 + b_1 D^{b_2} H^{b_3}$$

Figure 8.3

Plotted residuals for the linear and non-linear model.



listed in Appendix 3 range from 1.65 to 2.34. Although it had been expected (page 104) that the exponent would tend to be somewhat greater than 2, this had been subject to the degree of correlation between D and H - which can be seen from Appendix 2 to be generally poor - and to uncertainty about the possible effects of variations in stem form. Values of less than 2 did not therefore invalidate the model, and the range of variation itself justified the decision to allow the exponent of D to vary. The standard deviations of the parameter estimates indicated that 23 out of 24 were significantly different from 2 (for $p = 0.05$).

The expectation concerning the exponent of H (i.e., $b_3$ above) had the somewhat sounder basis that taper was generally positive (see page 104). The values shown in Appendix 3 range from 0.47 to 0.94, and all were significantly different from 1 (for $p = 0.05$). The major difference in behaviour between the linear and non-linear model - i.e., a trend of V with H which was convex upwards rather than linear - was therefore present for all data sets.

The estimates of parameter $b_1$ vary from 0.000027 to 0.00049, with most in the range 0.00004 to 0.0001. This represents considerably more variation than for the comparable parameter in a combined-variable model, where the regression coefficient is strongly correlated with form factor. In the non-linear model, however, $b_1$ was strongly correlated with the exponents of D and H, and variation in these exponents led to much wider variations in the estimates of $b_1$ than for the linear case.

The values for $b_0$ shown in Appendix 3 are predominately negative. Kozak (1973) has commented that in many cases the magnitude and sign of the constant term in a regression model may not be of any significance when data for very small trees is lacking; however in this case some of the data sets did include relatively small trees. The use of merchantable volume can be expected to lead to a negative constant term, in that merchantable volume will become zero for trees below a certain size. The largest negative values of $b_0$ were associated with the data sets lacking observations for the smallest sizes, which partly supports Kozak's (1973) comments, but the parameter estimates were still of the expected sign. All models yielded sensible values of predicted volume for the smallest trees in their data sets.

Despite the relatively wide variations in parameter estimates, all of the non-linear models behaved in a biologically sensible manner.

### Statistical Rigour

The statistical assumptions of homoscedasticity, independence and normality were tested for the non-linear model on each data set. Results are given in Table 8.2.

Of the 23 results obtained from Bartlett's test, 17 were non-significant and 6 significant at the 5% level. This proportion represented a significant departure from expec-

Table 8.2

Results of testing for heteroscedasticity, serial correlation and normality with the model $V = b_0 + b_1 D^{b_2} H^{b_3}$.

Key: NS not significant; -- no result (see p. 82);
* significant;
(+) significant positive; (-) significant negative.

| Locality | Species | No. Obs. | Hetero-scedas-ticity | Serial correl-ation | Normality Skewness | Normality Kurtosis |
|---|---|---|---|---|---|---|
| Old style data | | | | | | |
| 02 | 01 | 150 | NS | NS | NS | NS |
| 03 | 01 | 95 | NS | NS | NS | NS |
| 07 | 01 | 86 | -- | * | (+) | (+) |
| 02+03+07 | 02 | 631 | NS | * | NS | (+) |
| 02+03 | 03 | 160 | NS | * | NS | NS |
| New style data | | | | | | |
| 011 | 01 | 65 | * | NS | NS | NS |
| 02+022 | 01 | 101 | NS | * | (-) | (+) |
| 0211 | 01 | 54 | NS | NS | (-) | NS |
| 031 | 01 | 121 | NS | * | NS | NS |
| 07 | 01 | 80 | NS | * | NS | NS |
| 091 | 01 | 157 | * | * | NS | NS |
| 011 | 02 | 96 | NS | NS | NS | NS |
| 02+0211+022 | 02 | 143 | NS | * | NS | NS |
| 031 | 02 | 111 | NS | * | NS | NS |
| 07 | 02 | 168 | NS | * | NS | NS |
| 091 | 02 | 156 | * | * | NS | (+) |
| 02+022 | 03 | 98 | NS | * | (+) | NS |
| 0211 | 03 | 54 | NS | * | NS | (+) |
| 031 | 03 | 126 | NS | * | NS | NS |
| 022 | 06 | 44 | NS | NS | NS | NS |
| 091 | 06 | 156 | * | * | NS | NS |
| 011 | 68 | 108 | NS | * | NS | NS |
| 031 | 68 | 131 | * | * | NS | NS |
| 091 | 68 | 153 | * | * | NS | NS |

tation due to chance alone, indicating that some degree of heteroscedasticity was present. The untransformed variances for the data set used in validating the weighting function (see Chapter 7) again showed similar trends, but for the data sets giving significant results the variances for the transformed observations showed no consistent trends with $D^2H$. The remnant heteroscedasticity was accepted as the price of using the same model and weighting function for all data sets. Some trials were carried out with alternative weighting functions, as discussed below, but no significant improvement in heteroscedasticity was achieved.

Significant serial correlation was present in 18 out of the 24 data sets. As discussed previously this was not unexpected, because of the type of cluster sampling used during the data collection, even for the old style data. Although the presence of serial correlation reduced the efficiency of the parameter estimates, the estimates were unbiased (Johnston, 1963); degrees of freedom for hypothesis testing were reduced to an unknown extent, but this was less important in view of the general lack of exact testing methods for non-linear models. There appeared to be little scope for improving model specification, and methods of reducing serial correlation such as culling the data would have lost information without necessarily increasing the scope for hypothesis testing. The presence of serial correlation was therefore accepted.

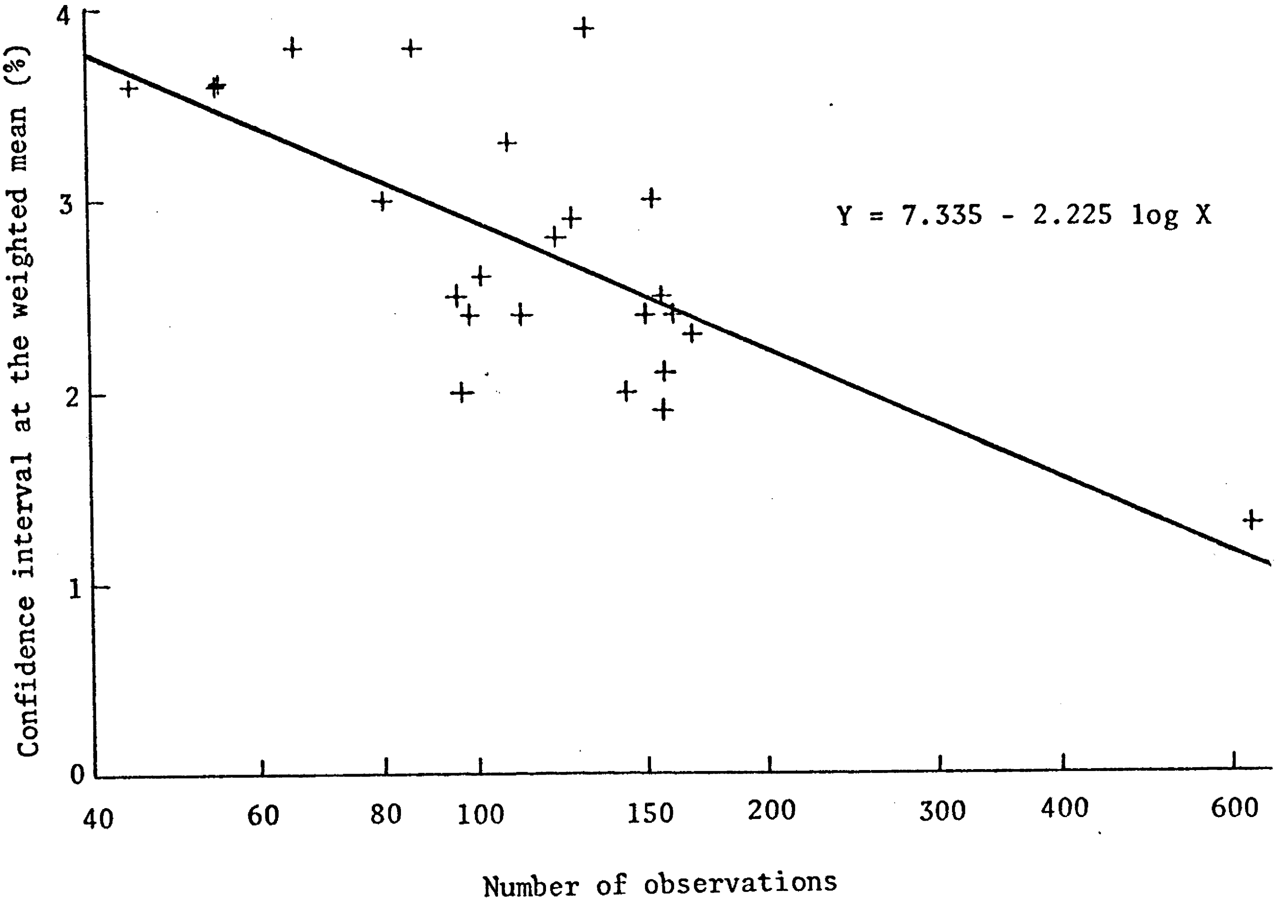
Four of the 24 data sets showed significant skewness at the 5% level; this was considered to be an acceptably low rate of non-normality. Moreover, with two cases each of significant positive and significant negative skewness, there was no evidence of a systematic departure from normality. This made it unlikely that any improvement would be produced by corrective action such as transforming the dependent variable.

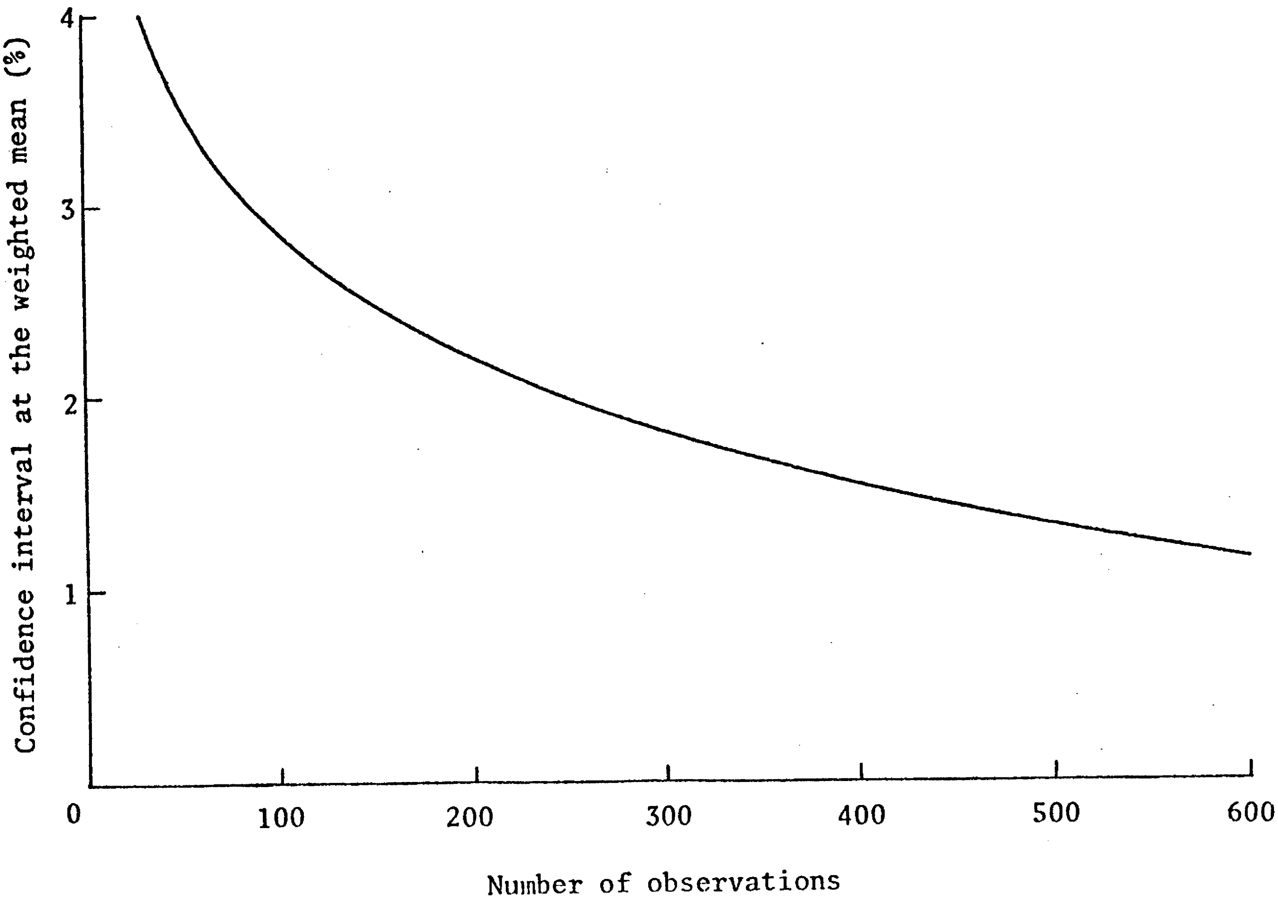
There were indications of systematic leptokurtosis, with all five of the significant results for kurtosis being positive. Earlier trials with untransformed deviates had confirmed that uncorrected heteroscedasticity did introduce leptokurtosis, because of the large numbers of smaller trees with relatively low deviations. Powers of $D^2H$ greater than 2 were therefore tested as weighting functions, but they were unsuccessful in reducing either leptokurtosis or heteroscedasticity. This level of non-normality was therefore also accepted.

## Precision of Estimate

As noted earlier (page 74), the development of non-linear model theory has not yet produced exact methods of interval estimation for predictions from a model. The problem was compounded in the case of the Northern Territory data by the violation of the statistical assumptions for ordinary least squares, especially the high level of serial correlation which was present. However some indications of

Figure 8.4
Relationship between 95% confidence interval at the weighted mean (weighted by $1/D^2H$) and number of observations. The lower curve shows the relationship on a linear scale. Confidence interval away from the mean would be wider than shown here.



the precision of volume estimate was considered desirable.

Williams (1959), Beale (1960) and Draper and Smith (1966) have all discussed the use of linear methods to obtain approximate interval estimates for the estimated parameters in a non-linear model. Linear methods were therefore used by analogy to obtain approximate confidence intervals for predicted volume.

The standard linear formula for confidence limits (Freese, 1964) includes terms which have no meaningful parallel for a non-linear model. However, if confidence limits at $\bar{Y}$ are to be calculated the formula reduces to

$$t\sqrt{\text{Residual MS }(1/n)}$$

This formula was used to calculate approximate 95% confidence limits at weighted mean Y (weighted by $1/D^2H$) for each data set, by assuming approximate degrees of freedom in each case of (n-4). Results are given in Table 8.3, expressed as percentages of the weighted mean in each case.

Because of the approximate nature of the estimates, no attempt was made to draw detailed conclusions for each data set. Instead an empirical relationship between confidence interval and number of observations was produced (Figure 8.4) as a general guide to the behaviour of precision with changes in the number of observations. The effect of differences in variance between data sets was ignored because of the approximate nature of the estimates. Some indication has been provided in Table 8.3 - by linear analogy - of the type of increase in confidence interval which could occur at

Table 8.3

Estimated precision for the final models: 95% confidence intervals at weighted mean Y (weighted by $1/D^2H$), expressed in percent.

| Locality | Species | n | Precis. | Locality | Species | n | Precis. |
|---|---|---|---|---|---|---|---|
| Old style data | | | | 011 | 02 | 96 | 2.0 |
| 02 | 01 | 150 | 2.4 | 02+0211+022 | 02 | 143 | 2.0 |
| 03 | 01 | 95 | 2.5 | 031 | 02 | 111 | 2.4 |
| 07 | 01 | 86 | 3.8 | 07 | 02 | 168 | 2.3 |
| | | | | 091 | 02 | 156 | 1.9 |
| 02+03+07 | 02 | 631 | 1.3 | | | | |
| | | | | 02+022 | 03 | 98 | 2.4 |
| 02+03 | 03 | 160 | 2.4 | 0211 | 03 | 54 | 3.6 |
| | | | | 031 | 03 | 126 | 2.9 |
| New style data | | | | | | | |
| 011 | 01 | 65 | 3.8 | 022 | 06 | 44 | 3.6 |
| 02+022 | 01 | 101 | 2.6 | 091 | 06 | 156 | 2.5 |
| 0211 | 01 | 54 | 3.6 | | | | |
| 031 | 01 | 121 | 2.8 | 011 | 68 | 108 | 3.3 |
| 07 | 01 | 80 | 3.0 | 031 | 68 | 131 | 3.9 |
| 091 | 01 | 157 | 2.1 | 091 | 68 | 153 | 3.0 |

Note: (i) Confidence intervals away from the mean would be wider than shown above. Some indication of the type of variation which could be expected can be obtained from the following confidence intervals, calculated for the linear combined-variable model fitted to the first data set in the above table:

| | V | Confidence Interval |
|---|---|---|
| | 0.1 | 7.5% |
| (weighted mean) | 0.268 | 2.5% (cf. 2.4% for non-linear) |
| | 1.0 | 3.9% |
| | 2.0 | 4.3% |

(ii) Serial correlation present in the data would reduce degrees of freedom by unknown amounts and consequently increase confidence intervals. The above figures therefore represent approximate minimum estimates only.

values away from the mean. Confidence intervals for estimated volume of an individual tree - rather than for the mean of a large number - would of course be considerably wider than shown in the table.

## Discussion

The non-linear model was accepted as the final tree volume model for the Northern Territory data. The violation of the statistical assumptions inherent in the data would have applied equally to a linear model, thereby nullifying any potential advantages from the exact methods of interval estimation available with linear models. The non-linear model showed the expected type of behaviour for merchantable volume and had a better overall fit to the data, thus giving superior performance as a point estimator.

# PART IIC : APPLICATION OF THE MODELS

## CHAPTER 9 : PRACTICAL CONSIDERATIONS

The development of final volume models completes one stage in the process of obtaining volume estimates for Northern Territory forests. The next stage of applying the models to existing forest inventory data involves a number of practical considerations arising from the nature of both the volume and the inventory data.

### (i) INTERNAL DIFFERENCES WITHIN THE DATA

The structural forest types used for stratification in the Northern Territory are described in Chapter 2. Because of problems of consistency in photo-interpretation, a final subdivision based on forest types was not considered appropriate, and groupings by species were used. Nevertheless it was of interest to determine the nature and extent of any significant differences associated with forest type.

Partitioning the data by structural forest types within species for each locality produced a large number of data sets, as shown in Table 9.1. Many of the data sets were very small, but a majority (81 out of 129) included 10 or more observations: these were chosen for the analyses as a comparison between complete coverage of the data and the use of excessively small data sets. Covariance analyses were

Table 9.1

Distribution of the data by structural forest types within species for each locality.

Key to locality and species codes: Appendix 1.

Key to forest type codes: Table 2.1, page 24.
The first 3 or 4 digits give the combined height and crown closure code; the separate digit at the end is the soil drainage code.

O L D   S T Y L E   D A T A

| Forest type code | Locality and species code 02 | | | 03 | | | 07 | |
|---|---|---|---|---|---|---|---|---|
| | 01 | 02 | 03 | 01 | 02 | 03 | 01 | 02 |
| 011 1 | 4 | 19 | | | | | | |
| 011 2 | 42 | 41 | 25 | 18 | 12 | | 23 | 189 |
| 011 3 | 66 | 23 | 18 | | | | | |
| 021 2 | 16 | 5 | 14 | 31 | 23 | 11 | 42 | 90 |
| 021 3 | 13 | 10 | | | | | | |
| 031 2 | 8 | 4 | 12 | 20 | 37 | 36 | 21 | 141 |
| 031 3 | 1 | 6 | 19 | | | | | |
| 041 2 | | | | 26 | 31 | 25 | | |

N E W   S T Y L E   D A T A

| Forest type code | Locality and species code 011 | | | 02 | | | 0211 | | | 022 | | | | 031 | | | | 07 | | 091 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 02 | 03 | 01 | 02 | 03 | 01 | 02 | 03 | 01 | 02 | 03 | 06 | 01 | 02 | 03 | 68 | 01 | 02 | 01 | 02 | 06 | 63 |
| 0021 2 | 5 | | | | | | | | | | | | 12 | | | | | | 1 | | | 8 | |
| 0021 3 | | | 2 | | | | | | | | | | | | | | | | | | | | 36 |
| 0021 4 | | | 4 | | | | | | | | | | | | | | | | | | | | 21 |
| 0021 7 | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 0211 2 | 1 | 11 | | | | | | | | | | 2 | 2 | | | | | | | | | 3 | |
| 0031 2 | 42 | 32 | | | | | | | | 6 | 10 | 4 | 25 | | 1 | | 1 | 4 | 7 | 66 | 36 | 94 | |
| 0031 3 | | | 41 | | | | | | | | | | | | | | | | | | | | 31 |
| 0031 4 | | | 6 | | | | | | | | | | | | | | 84 | | | | | | 35 |
| 0311 2 | 16 | 53 | | | | | | | | 20 | 15 | 9 | 3 | 51 | 88 | 88 | | | | 85 | 106 | 25 | |
| 0311 3 | | | 10 | | | | | | | 8 | | | | | | | | | | | | | |
| 0311 4 | | | 8 | | | | | | | | | | | | | 1 | | | | | | | 9 |
| 0041 1 | | | | | | | | | | | | | | | | | | 1 | 6 | | | | |
| 0041 2 | | | | | | | | | | | 8 | 12 | 2 | | 2 | 2 | | 10 | 95 | 1 | 1 | 19 | |
| 0041 3 | | | | | | | | | | | | | | | | | | | | | | | 10 |
| 0041 4 | | | 37 | | | | | | | | | | | | | | | | | | | | 7 |
| 0411 2 | | | | 9 | | | 18 | 8 | 13 | 8 | 11 | 17 | | 62 | 16 | 34 | | | | 5 | 13 | 5 | |
| 0411 3 | | | | | | | | | | 2 | | | | | | | | | | | | | |
| 0411 4 | | | | | | | | | | | | | | | | | 11 | | | | | | |
| 4111 2 | | | | 48 | 45 | 54 | | | | | | | | 8 | 4 | 1 | | | | | | | |
| 0051 1 | | | | | | | | | | | | | | | | | | 64 | | | | | |
| 0051 2 | | | | | | | | | | | | | | | | | | | 33 | | | 2 | |
| 0511 1 | | | | | | | | | | | | | | | | | | | 26 | | | | |
| 0511 2 | | | | | | | 36 | 46 | 41 | | | | | | | | | | | | | | |
| 0511 4 | | | | | | | | | | | | | | | | | 35 | | | | | | |

carried out on all locality-species groups which were represented by two or more forest types with at least 10 observations.

The linear $D^3$ model, weighted by $1/(D^2H)^2$ was used for the analyses. As with the earlier covariance analyses by species, no specific allowance was made for possible effects of serial correlation on degrees of freedom for the F-tests: preliminary trials again indicated that these effects became important only in borderline cases.

Results of the analyses are given in Table 9.2. Sixteen of the 26 groupings showed significant differences among forest types at the 5% level. Individual regressions within each group were examined, but there were no obvious or consistent trends in the regression coefficients with changes in either the crown closure or predominant height classes for the structural forest types.

There was a possibility that the differences between forest types were associated with other variables included in the data. Variables other than D, H and V included: plot basal area (old style data only), total tree height (rather than length of merchantable bole), bark thickness and stump height. Simple models were developed from the combined-variable equation to include these variables, either from comparable models in the literature - e.g., models including basal area used by Leech (1973) and Alexander _et al_. (1975) - or from various simple assumptions. Covariance analyses were then repeated using these models to

Table 9.2

Results of covariance analyses by forest type. The regression model used was:

$$V = b_0 + b_1 D^2 H + b_2 D^3$$

weighted by $1/(D^2H)^2$.

| Locality | Species | Sig. differences in: coeffs. | constants |
|---|---|---|---|
| 02 (old) | 01 | * | |
| | 02 | NS | * |
| | 03 | * | |
| 03 (old) | 01 | NS | NS |
| | 02 | NS | * |
| | 03 | NS | NS |
| 07 (old) | 01 | NS | * |
| | 02 | * | |
| 011 | 01 | NS | * |
| | 02 | * | |
| | 68 | NS | * |
| 0211 | 01 | * | |
| | 03 | NS | NS |
| 022 | 02 | NS | NS |
| | 03 | NS | NS |
| | 06 | NS | NS |
| 031 | 01 | * | |
| | 02 | NS | * |
| | 03 | NS | NS |
| | 68 | NS | NS |
| 07 | 01 | NS | NS |
| | 02 | * | |
| 091 | 01 | NS | * |
| | 02 | NS | * |
| | 06 | * | |
| | 68 | NS | NS |

see if the number of significant differences between forest types was reduced by the inclusion of any of these variables.

The models used and the results obtained are shown in Table 9.3. An inferior weighting function - i.e., $1/D^2H$ instead of $1/(D^2H)^2$ - was used for the analyses, but repeating them with a new weighting function was considered unwarranted. Analyses with the combined-variable model were included for comparison, and these showed a relatively high degree of similarity to the results given in Table 9.2 for the $D^3$ model weighted by $1/(D^2H)^2$. Results of the analyses with the additional models showed no reduction in the number of significant diferences with the combined-variable model, indicating that the differences between forest types were not associated with any of the additional variables.

It was unclear whether the observed differences between forest types reflected real differences in the field, or whether they were a product of the sampling methods used. The concentration of sampled trees in limited areas, especially for the new style data, could well have highlighted localised differences which were not necessarily generalisable across the whole of each forest type. It will be possible to resolve this point only after more representative data are collected.

The data sets for individual forest types were tested for departures from the statistical assumptions, within the limitations of the reduced numbers of observations

Table 9.3

Results of covariance analyses by forest type with additional regression models.
(Key: coef = coefficients; cons = constants.)
The models used were:

Model 1 : $V = b_o + b_1 D^2H$

Model 2 : $V = b_o + b_1 D^2H + b_2 D^2H.BA$

Model 3 : $V = b_o + b_1 D^2H + b_2 D^2H(H/H_{tot})$

Model 4 : $V = b_o + b_1 (dub)^2 H$

Model 5 : $V = b_o + b_1 (D_{br.ht.+stump})^2 H$

| Loc. | Sp. | Model 1 coef | Model 1 cons | Model 2 coef | Model 2 cons | Model 3 coef | Model 3 cons | Model 4 coef | Model 4 cons | Model 5 coef | Model 5 cons |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 02 | 01 | * | | * | | * | | * | | * | |
| (old) | 02 | * | | unable to | | * | | NS | * | * | |
| | 03 | * | | fit model | | * | | * | | NS | NS |
| 03 | 01 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| (old) | 02 | * | | NS | * | NS | * | * | | * | |
| | 03 | * | | * | | NS | NS | * | | * | |
| 07 | 01 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| (old) | 02 | * | | * | | * | | * | | * | |
| 011 | 01 | NS | * | | | NS | * | NS | NS | NS | * |
| | 02 | * | | | | * | | * | | * | |
| | 68 | NS | * | | | NS | * | NS | * | NS | * |
| 0211 | 01 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| | 03 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| 022 | 02 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| | 03 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| | 06 | NS | NS | | | * | | NS | NS | NS | NS |
| 031 | 01 | NS | * | | | NS | * | NS | * | NS | * |
| | 02 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| | 03 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| | 68 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| 07 | 01 | NS | * | | | * | | NS | * | NS | * |
| | 02 | * | | | | NS | NS | * | | * | |
| 091 | 01 | NS | NS | | | NS | NS | NS | NS | NS | NS |
| | 02 | NS | * | | | NS | * | NS | * | NS | * |
| | 06 | NS | NS | | | * | | * | | NS | NS |
| | 68 | NS | NS | | | NS | NS | NS | NS | NS | NS |

normality at least were present at levels somewhat similar to those detected among the species groups. Grouping apparently incompatible forest types within each species did not seem to cause marked changes in the incidence of these problems: grouping by species was also free from the uncertainties in forest type classification using aerial photographs, and avoided the problem of data sets with very small numbers of observations.

(ii) REPRESENTATIVENESS OF THE DATA

The importance of obtaining a representative sample of volume data was discussed in Chapter 3. The old style data, which were collected from clear felled inventory plots, represented an objective subsample, and the volume models produced from these data are applicable to the population covered by the old style inventory data. Clustering the observations into plots may have been the cause of the high levels of serial correlation in the data, but this would have merely overestimated precision without introducing bias.

For the new style data, however, the models developed on the volume data will not necessarily be applicable to the same population as the inventory data, because the former were collected by subjective sampling. As discussed in Chapter 4, the volume data were used in this study to test various volume models, and if additional data were collected by objective methods it is likely that similar models could be fitted successfully.

Some comparison was possible between the old and new style methods of data collection. Within the old style data, one locality (Gove) was covered by both clear felled plots (old style locality 07) and by subjective sampling (old style locality 070): covariance analyses within each species showed that the two types of data gave significantly different regressions.

As an additional empirical test, both old and new style data for all localities on Melville and Bathurst Islands were combined within species and non-linear models fitted. Differences between actual and predicted mean volumes were then calculated for data from each locality. Results for species 02 were:

| Locality | No. obs. | Mean actual volume | Mean predicted volume | Difference |
|---|---|---|---|---|
| 02(old) | 108 | 0.365 | 0.396 | +0.031 |
| 03(old) | 103 | 0.520 | 0.547 | +0.027 |
| 02 | 45 | 1.195 | 1.102 | -0.093 |
| 0211 | 54 | 0.612 | 0.587 | -0.025 |
| 022 | 44 | 0.352 | 0.340 | -0.012 |

Although species 02 was able to be combined for each locality on Melville and Bathurst Islands within old and new style data separately, an apparent systematic bias existed between both types of data. Similar results were obtained with species 01 and 03. These results were almost certainly associated with the apparent bias in d.b.h. noted earlier (page 54).

If objective sampling is accepted as representative for a particular area, then the apparent differences between data collected by objective and subjective methods must cast some doubt on the representativeness of the latter. The differences for Melville and Bathurst Islands may have been due to changes in measurement methods - although as discussed in Chapter 4 no evidence of serious differences could be located - but the differences for the Gove area occurred with all old style data.

(iii) EXTRAPOLATION BEYOND THE DATA

(a) Tree Sizes Beyond the Data

Carron (1968) has recommended for volume tables compiled by graphical methods that extrapolation be usually limited to one height-diameter cell in each direction and the values used with caution. Mathematical models are easily extrapolated beyond the range of their development data, and over thirty years ago Stoate (1945) cautioned against the practice. The problem is particularly relevant to merchantable bole volume for hardwood trees, where very short merchantable boles may occasionally be associated with very large diameters, and trees of this type may not have been included in the volume data. As Bowling (1951) has noted, widening the range of data in such cases may involve the haphazard task of locating sample trees of unusual dimensions.

In most cases an existing volume model will be extrapolated beyond the data because this provides the best available estimate. Volume data collected from uneven-aged forests will reflect the size distribution of the population and include only limited numbers of large trees, and the Northern Territory data are no exception. Extrapolated estimates for larger sizes will be most satisfactory when the volume model shows a good fit at the upper end of the range and gives sensible results when extrapolated; this was one reason for adopting the non-linear model rather than the linear D model as the final volume model.

The range of volume data can be increased without biasing the volume estimate by selecting sample trees on the basis of the independent variables (e.g., equal numbers in each diameter class), provided only that the selected trees are a true random sample of all trees in the size class (Freese, 1967). Although the new style data were collected by size classes, random sampling was not used; suggested sampling methods for future data collection are discussed in the next chapter.

(b) New Localities, Species and Forest Types

The covariance analyses described in Chapter 7 showed that in most cases there were significant differences between localities for a given species, and the results presented in the first section of this chapter indicate that significant differences between forest types may also exist. For this reason it would appear desirable to collect volume data within each new area covered by forest inventory, and to obtain a reasonable coverage of the major species and forest types included in the inventory.

Species of minor occurrence represent a practical problem in obtaining adequate numbers of observations, and in many cases such species may not be of sufficient importance to warrant the cost of extensive data collection. The most expedient approach is to combine all data for these species under the heading of "other species". Observations for species of minor occurrence were included in the old style data, and the last two models shown in Appendix 3 are for these species; they were not included in any of the analyses described in this study and are provided only for the sake of completeness. In view of the apparent differences betwen the old and new style data it would seem advisable to collect data for species of minor occurrence under the new style measurement system.

# PART III : DISCUSSION

## CHAPTER 10 : THE STUDY IN PERSPECTIVE

This study must be viewed in the broader context of stand volume estimation as a whole. Relevant considerations include: the importance of sampling error in the volume models as part of the overall error in final volume estimates; the number of observations required to achieve a given precision; and the scope for additional work on some aspects of volume estimation.

### (i) THE VOLUME MODEL ERROR COMPONENT

Different sources of error in the final volume estimate have been discussed by Lewis (1957) for exotic conifers in New Zealand and Batini and Williamson (1971) for hardwood forests in Western Australia. Formulae have been developed by Cunia (1965) and Meng (1972) to include the effects of error components such as field plot sampling error, volume model sampling error and the effects of grouping tree measurements into discrete classes. Meyer (1963) has drawn attention to the effect of errors in the forest area estimate.

Inventory methods used in the Northern Territory have been described in Chapter 2. Some of the main sources of uncertainty in the final volume estimate include:

- sampling error in the estimation of areas of forest type strata from aerial photographs;

- inventory field plot sampling error;

- sampling error for the volume model;

In addition there are less quantifiable sources of error such as possible inconsistencies in photo interpretation, uncertainties in merchantability classification in the field, and measurement errors.

There has been variation in numbers of photo and field plots between inventories, but for the more recent new style inventories the numbers were generally such as to achieve theoretical sampling errors in the vicinity of 2% for the estimated total area of commercial forest, and approximately 5% for the field plots component (at the 95% level). If an approximate allowance of 5% is made for the errors of unknown size introduced by other factors, then some indication of the effect of the volume model error component can be obtained. A total error in volume estimate can be roughly estimated by summing variances (Freese, 1967) for different levels of volume error as follows:

(i) for a volume model error of 10%:

$$\text{total error} = \sqrt{10^2 + 2^2 + 5^2 + 5^2} = 12.4\%$$

(ii) for a volume model error of 5%:

total error = 8.9%

(iii) for a volume model error of 2%:

total error = 7.6%

It can be seen that for assumed error components of this order of size that a reduction in volume model error from 10% to 5% would produce a reduction of approximately 3.5% in the overall error, but that a further reduction of 3% would produce a further improvement of only 1.3% in total error. In the absence of precise data on the size of various error component, it would appear that if volume model error were kept down to about 5% it would not unduly degrade the overall error in volume estimate. The majority of volume models developed cover a single species of major occurrence within a single locality, and the total error would therefore apply to the volume estimate for one such species.

## (ii) SAMPLING LEVELS FOR SPECIFIED PRECISION

The empirical relationship developed between confidence interval and number of observations (Figure 8.4, page 126) provides some guide to the sampling levels required to achieve a specified precision. As indicated in Table 8.3 (page 124), confidence interval away from the mean would be wider than shown; when the additional effect of reductions in degrees of freedom due to serial correlation is also taken into account it would probably be necessary to approximately double the tabulated figures to obtain a realistic estimate of overall precision.

On this basis, the results shown in Figure 8.4 indicate that between 100 and 200 observations would generally be required to achieve a nominal precision of 2.5%, i.e., a probable precision in the vicinity of 5% in practice. In view of the usually significant differences between localities, this number of observations would be required for each major species in any new locality covered by forest inventory. If the differences between forest types discussed in Chapter 9 prove to be important, it may be necessary to also collect increased numbers of observations within major forest types.

## (iii) ASPECTS MERITING FURTHER WORK

### (a) Sampling Methods

In order to maximise the value of time spent on the collection of volume data, the sample should be representative of the population covered by the associated inventory. This is most conveniently achieved by taking measurements within an objectively selected subsample of the inventory field plots, as was done with the old style data. To avoid an inadequate representation of the larger trees, some simple sampling prescription could be applied - e.g., to measure only trees above a certain diameter on all plots and include smaller sizes on every nth plot. More complicated prescriptions involving several size classes would improve data distribution, but could be difficult to apply in practice.

Considerable serial correlation was present even among the old style data. The plot size used was 0.2 ha, and it appears likely that this size may have produced too high a level of "clustering" in the data. A new method of resource inventory begun in 1974 used a plot size of 0.1 ha, which should reduce the level of serial correlation. If the problem persists it may be necessary to limit volume measurements to an even smaller subplot within the inventory plot.

(b) Specific Volume Models

The same volume model and weighting function were applied in this study to all data sets. As discussed earlier, the non-linear volume model gave a generally good fit to the data, and its response against both diameter and height appeared to be in keeping with the expected behaviour of merchantable bole volume. However the use of $1/(D^2H)^2$ as a general weighting function, while satisfactory for the linear $D^3$ model, appeared somewhat less satisfactory for the non-linear model (Table 8.2, page 122); although there seemed to be no clear trends in the remnant heteroscedasticity, the improved fit of the non-linear model among the larger sizes apparently altered the relationship between variance and $D^2H$.

There may therefore be scope for the development of specific weighting functions for individual data sets, either for existing data or for observations collected in the future. Data for new species and localities may not necessarily be best served by the non-linear model developed in this study, and it may prove necessary in the future to use more than one model form.

(c) Utilisable Volume

The volume modelled in this study was gross merchantable bole volume potentially suitable for chipwood. This represents a maximum estimate of utilisable volume, which is modified by factors such as merchantability standards and the incidence of defect.

Merchantability codes were included in the data, as described in Chapter 4, but were used in this study only to reject unmerchantable trees. Because of the limited numbers of observations in some data sets and the somewhat subjective nature of the merchantable gradings, no distinctions were made between different merchantability classes. This point may require further investigation at a stage when product grading becomes important.

Estimates of volume to various small end diameters and of the volume of internal defect were also calculated from the raw data. Some preliminary development of conversion factors based on these data were carried out during the study, but suitable final models were not produced within the time available. It is hoped that these aspects will be developed further in the future.

(iv) DISCUSSION AND CONCLUSIONS

This study has provided the first comprehensive set of tree volume models for hardwood data from the Northern Territory. The models developed on the old style data collected before 1970 may be accepted as representative of the populations covered by the associated forest inventories, and the model development carried out on the new style data has shown that the same type of model can be successfully applied to these data also.

The non-linear volume model of the form

$$V = b_0 + b_1 D^{b_2} H^{b_3}$$

was successfully fitted to a wide range of hardwood volume data for different species and localities throughout the "Top End" of the Northern Territory. The weighting function $1/(D^2H)^2$, based on the one general relationship

$$s^2 = k(D^2H)^2$$

for all data, was successfully used with a non-linear regression fitting program.

The data showed relatively minor departures from the ordinary least squares assumptions of homoscedasticity and normality. The assumption of independence of errors, however, did not hold, with significant levels of first order serial correlation being detected for most data sets; this did not appear to be a consequence of model misspecification but rather was probably a result of the sampling methods used for data collection. The only major effect of the serial correlation in the data was to reduce degrees of freedom by unknown amounts and cause some overestimation of precision in volume estimates, without introducing bias.

Weighted covariance analyses were carried out with the linear model

$$V = b_0 + b_1 D^2H + b_2 D^3$$

and the same weighting function as above. These analyses showed that in most cases there were significant differences in the relationship of volume with diameter and height for the same species from different localities. There were also indications of significant differences due to forest type. Comparable methods of analysis were not available for non-linear models and, in view of the generally similar - though inferior - fit to the data shown by the linear model, the findings were assumed to be applicable to the non-linear model as well.

As best as can be determined from the literature, this study represents only the second use of an intrinsically non-linear model structure with tree volume data - the first being work by Turner (1972) - and its first successful use as a weighted volume model. It appears to be the first application of non-linear regression methods to tropical hardwoods. The study has shown that non-linear tree volume models can be successfully applied to heterogeneous data for a range of hardwood species occurring in tropical woodland in the Northern Territory.

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# APPENDIX 1

## KEY TO LOCALITY AND SPECIES CODES

### Locality Codes

#### (i) Old Style Data

| | |
|---|---|
| Melville and Bathurst Islands | 02 |
| Garden Point | 03 |
| Gove | 07 |
| Gove (single trees) | 070 |

#### (ii) New Style Data

| | |
|---|---|
| Lake Evella | 011 |
| Melville and Bathurst Islands | 02 |
| Melville Island West - Garden Point | 0211 |
| Melville Island East | 022 |
| Murgenella | 031 |
| Gove | 07 |
| Maningrida | 091 |

### Species Codes

| | |
|---|---|
| Eucalyptus miniata | 01 |
| Eucalyptus tetrodonta | 02 |
| Eucalyptus nesophila | 03 |
| Eucalyptus bleeseri | 06 |
| Melaleuca spp. | 68 |

# APPENDIX 2

## STAND TABLES FOR SPECIES OF MAJOR OCCURRENCE

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

MELVILLE AND BATHURST ISLANDS, LOCALITY CODE 02 OLD STYLE DATA

01 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 2 | 6 | 9 | 9 | | | | | | 26 |
| 25 | | 1 | 9 | 15 | 9 | 1 | | | | | 35 |
| 30 | | 2 | 8 | 10 | 11 | 1 | 2 | | | | 34 |
| 35 | | 1 | 3 | 13 | 8 | | 1 | | | | 26 |
| 40 | | 1 | 2 | 5 | 6 | 4 | 1 | | | | 19 |
| 45 | | | | 2 | 2 | 1 | 1 | | | | 6 |
| 50 | | | | | 1 | | | | | | 1 |
| 55 | | | 1 | | 1 | | | | | | 2 |
| >=57.5CM | | | | | 1 | | | | | | 1 |
| LENGTH CLASS TOTAL | | 7 | 29 | 54 | 48 | 7 | 5 | | | | |

NO. OF SAMPLES = 150

MEAN DIAMETER = 30.5 CM MAX = 64.2 CM MIN = 20.3 CM

MEAN LOG LENGTH = 8.5 M MAX = 14.6 M MIN = 4.6 M

02 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 3 | 2 | 12 | 10 | 2 | 1 | | | | 30 |
| 25 | | 2 | 6 | 9 | 9 | 5 | | 3 | | | 34 |
| 30 | | 1 | 2 | 3 | 6 | 1 | 3 | | | | 16 |
| 35 | | 1 | 2 | 1 | 2 | 5 | 1 | 2 | | | 14 |
| 40 | | | | 1 | 4 | | 1 | 1 | | | 7 |
| 45 | | | 2 | 1 | 1 | | | 1 | | | 5 |
| 50 | | | | | | | | 1 | | | 1 |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | 1 | | | | | 1 |
| LENGTH CLASS TOTAL | | 7 | 14 | 27 | 32 | 14 | 6 | 8 | | | |

NO. OF SAMPLES = 108

MEAN DIAMETER = 28.3 CM MAX = 71.1 CM MIN = 20.3 CM

MEAN LOG LENGTH = 9.5 M MAX = 16.8 M MIN = 3.4 M

03 EUCALYPTUS NESOPHILA

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | 2 | 11 | 3 | | | | | | 16 |
| 25 | | 1 | 3 | 10 | 14 | 1 | | | | | 29 |
| 30 | | | | 6 | 8 | 1 | | | | | 15 |
| 35 | | | 2 | 3 | 3 | 2 | 1 | | | | 11 |
| 40 | | | 1 | 5 | 1 | 1 | | | | | 8 |
| 45 | | | 1 | 2 | | 3 | | | | | 6 |
| 50 | | | | | | 1 | | | | | 1 |
| 55 | | | | | | | | | | | |
| >=57.5CM | | 1 | 1 | | | | | | | | 2 |
| LENGTH CLASS TOTAL | | 2 | 10 | 37 | 29 | 9 | 1 | | | | |

NO. OF SAMPLES = 88

MEAN DIAMETER = 30.2 CM MAX = 57.6 CM MIN = 20.6 CM

MEAN LOG LENGTH = 8.8 M MAX = 14.6 M MIN = 3.7 M

** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 7 | 4 | | | | | | | | 11 |
| 25 | 2 | 16 | 4 | 1 | 1 | | | | | | 24 |
| 30 | | 3 | 5 | | | | | | | | 8 |
| 35 | | 3 | 1 | | | | | | | | 4 |
| 40 | 2 | 1 | 2 | | | | | | | | 5 |
| 45 | | 1 | | | | | | | | | 1 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 4 | 31 | 16 | 1 | 1 | | | | | | |

NO. OF SAMPLES = 53

MEAN DIAMETER = 27.1 CM MAX = 43.9 CM MIN = 20.3 CM

MEAN LOG LENGTH = 4.8 M MAX = 12.4 M MIN = 2.4 M

**** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 12 | 14 | 32 | 22 | 2 | 1 | | | | 83 |
| 25 | 2 | 20 | 22 | 35 | 33 | 7 | | 3 | | | 122 |
| 30 | | 6 | 15 | 19 | 25 | 3 | 5 | | | | 73 |
| 35 | | 5 | 8 | 17 | 13 | 7 | 3 | 2 | | | 55 |
| 40 | 2 | 2 | 5 | 11 | 11 | 5 | 2 | 1 | | | 39 |
| 45 | | 1 | 3 | 5 | 3 | 4 | 1 | 1 | | | 18 |
| 50 | | | | | 1 | 1 | | 1 | | | 3 |
| 55 | | | 1 | | 1 | | | | | | 2 |
| >=57.5CM | | 1 | 1 | | 1 | 1 | | | | | 4 |
| LENGTH CLASS TOTAL | 4 | 47 | 69 | 119 | 110 | 30 | 12 | 8 | | | |

NO. OF SAMPLES = 399

MEAN DIAMETER = 29.4 CM MAX = 71.1 CM MIN = 20.3 CM

MEAN LOG LENGTH = 8.3 M MAX = 16.8 M MIN = 2.4 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

GARDEN POINT. LOCALITY CODE 03 OLD STYLE DATA

### 01 EUCALYPTUS MINIATA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | 1 | 5 | 4 | | | | | | 10 |
| 25 | | | 2 | 3 | 9 | 5 | | | | | 19 |
| 30 | | | 2 | 6 | 7 | 4 | 1 | 1 | 1 | | 22 |
| 35 | | | 2 | 5 | 3 | 3 | 4 | 2 | | | 19 |
| 40 | | | | | 3 | 3 | | 1 | | | 7 |
| 45 | | | | 1 | 1 | 1 | 2 | | 2 | 1 | 8 |
| 50 | | | | | 1 | 3 | 3 | | | | 7 |
| 55 | | | | | 1 | | | | | | 1 |
| >=57.5CM | | | | | | | 1 | 1 | | | 2 |
| LENGTH CLASS TOTAL | | | 7 | 20 | 29 | 19 | 11 | 5 | 3 | 1 | |

NO. OF SAMPLES = 95

MEAN DIAMETER = 33.2 CM MAX = 59.4 CM MIN = 20.3 CM

MEAN LOG LENGTH = 10.0 M MAX = 22.3 M MIN = 5.8 M

### 02 EUCALYPTUS TETRODONTA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 1 | 3 | 4 | 4 | | 1 | | | | 13 |
| 25 | | | 2 | 7 | 4 | 5 | 5 | | | | 23 |
| 30 | | 2 | 1 | 4 | 11 | 6 | 2 | 2 | 1 | | 29 |
| 35 | | | 1 | 1 | 3 | 1 | 5 | | 1 | | 12 |
| 40 | | | 1 | 3 | 5 | 2 | 1 | 1 | 1 | | 14 |
| 45 | | | | | 3 | 1 | 1 | | | | 5 |
| 50 | | | | 1 | | 2 | | | | | 3 |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | 1 | 1 | 1 | | | | | 1 | 4 |
| LENGTH CLASS TOTAL | | 3 | 9 | 21 | 31 | 17 | 15 | 3 | 3 | 1 | |

NO. OF SAMPLES = 103

MEAN DIAMETER = 32.1 CM MAX = 68.5 CM MIN = 20.8 CM

MEAN LOG LENGTH = 10.6 M MAX = 19.2 M MIN = 3.7 M

### 03 EUCALYPTUS NESOPHILA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | 2 | 4 | 3 | 1 | | | | | 10 |
| 25 | | 1 | 3 | 12 | 2 | 2 | 1 | | | | 21 |
| 30 | | 2 | 1 | 1 | 6 | 3 | 1 | | | | 14 |
| 35 | | | | 1 | 8 | | 2 | | | | 11 |
| 40 | | | 2 | 2 | 1 | 1 | | | | | 6 |
| 45 | | | | | 1 | | | | | | 1 |
| 50 | | | | 2 | | | | | | | 2 |
| 55 | | | | | 1 | 1 | 2 | | | | 4 |
| >=57.5CM | | 1 | | | 1 | | | | 1 | | 3 |
| LENGTH CLASS TOTAL | | 4 | 8 | 22 | 23 | 8 | 6 | | 1 | | |

NO. OF SAMPLES = 72

MEAN DIAMETER = 32.8 CM MAX = 74.9 CM MIN = 20.8 CM

MEAN LOG LENGTH = 9.2 M MAX = 17.1 M MIN = 3.7 M

### ** OTHER SPECIES **

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 2 | 1 | 1 | | | | | | | 4 |
| 25 | | | 2 | | 1 | | | | | | 3 |
| 30 | | 1 | 1 | 2 | | | | | | | 4 |
| 35 | | 1 | | 1 | | | | | | | 2 |
| 40 | | 1 | 2 | | | | | | | | 3 |
| 45 | | | | 2 | | | | | | | 2 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 5 | 6 | 6 | 1 | | | | | | |

NO. OF SAMPLES = 18

MEAN DIAMETER = 31.2 CM MAX = 45.2 CM MIN = 20.6 CM

MEAN LOG LENGTH = 6.3 M MAX = 10.4 M MIN = 3.7 M

### **** ALL SPECIES ****

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | 3 | 7 | 14 | 11 | 1 | 1 | | | | 37 |
| 25 | | 1 | 9 | 22 | 16 | 12 | 6 | | | | 66 |
| 30 | | 5 | 5 | 13 | 24 | 13 | 4 | 3 | 2 | | 69 |
| 35 | | 1 | 3 | 8 | 14 | 4 | 11 | 2 | 1 | | 44 |
| 40 | | 1 | 5 | 5 | 9 | 6 | 1 | 2 | 1 | | 30 |
| 45 | | | | 3 | 5 | 2 | 3 | | 2 | 1 | 16 |
| 50 | | | | 3 | 1 | 5 | 3 | | | | 12 |
| 55 | | | | | 2 | 1 | 2 | | | | 5 |
| >=57.5CM | | 1 | 1 | 1 | 2 | | 1 | 1 | 1 | 1 | 9 |
| LENGTH CLASS TOTAL | | 12 | 30 | 69 | 84 | 44 | 32 | 8 | 7 | 2 | |

NO. OF SAMPLES = 288

MEAN DIAMETER = 32.6 CM MAX = 74.9 CM MIN = 20.3 CM

MEAN LOG LENGTH = 10.1 M MAX = 22.3 M MIN = 3.7 M

N.T. LOG MEASUREMENT DATA
STAND TABLES BY SPECIES
GOVE. LOCALITY CODE 07 OLD STYLE DATA

01 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 1 | 4 | 2 | | | | | | | 7 |
| 15 | | 2 | 6 | 3 | 4 | | | | | | 15 |
| 20 | 1 | 3 | 6 | 9 | 7 | 3 | | | | | 29 |
| 25 | 1 | 1 | 5 | 12 | 4 | 1 | | 1 | | | 25 |
| 30 | | | 1 | 2 | 1 | | | | | | 4 |
| 35 | | 1 | 1 | | 1 | | | | | | 3 |
| 40 | | | | | 2 | | | | | | 2 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | 1 | | | | | | 1 |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 2 | 8 | 23 | 28 | 23 | 4 | | 1 | | | |

NO. OF SAMPLES = 86
MEAN DIAMETER = 21.5 CM MAX = 53.3 CM MIN = 10.2 CM
MEAN LOG LENGTH = 7.7 M MAX = 16.2 M MIN = 2.4 M

02 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 16 | 30 | 16 | 6 | | | | | | 68 |
| 15 | | 9 | 20 | 38 | 35 | 10 | 6 | | | | 118 |
| 20 | | 6 | 17 | 24 | 29 | 12 | 16 | 3 | 1 | | 108 |
| 25 | | 3 | 5 | 19 | 20 | 13 | 12 | 5 | 1 | | 78 |
| 30 | | 3 | 4 | 4 | 7 | 6 | 3 | 2 | 1 | | 30 |
| 35 | | | 2 | 2 | 6 | 2 | 3 | | | | 15 |
| 40 | | | | | | 1 | 2 | | | | 3 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 37 | 78 | 103 | 103 | 44 | 42 | 10 | 3 | | |

NO. OF SAMPLES = 420
MEAN DIAMETER = 19.3 CM MAX = 40.1 CM MIN = 9.1 CM
MEAN LOG LENGTH = 9.1 M MAX = 17.1 M MIN = 3.0 M

N.T. LOG MEASUREMENT DATA
STAND TABLES BY SPECIES
GOVE. LOCALITY CODE 07 OLD STYLE DATA

** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 2 | | | | | | | | | 2 |
| 15 | | 1 | | | | | | | | | 1 |
| 20 | | | 1 | 1 | | | | | | | 2 |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 3 | 1 | 1 | | | | | | | |

NO. OF SAMPLES = 5
MEAN DIAMETER = 15.9 CM MAX = 20.6 CM MIN = 10.2 CM
MEAN LOG LENGTH = 5.2 M MAX = 6.5 M MIN = 3.4 M

**** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 19 | 34 | 18 | 6 | | | | | | 77 |
| 15 | | 12 | 26 | 41 | 39 | 10 | 6 | | | | 134 |
| 20 | 1 | 9 | 24 | 34 | 36 | 15 | 16 | 3 | 1 | | 139 |
| 25 | 1 | 4 | 10 | 31 | 24 | 14 | 12 | 6 | 1 | | 103 |
| 30 | | 3 | 5 | 6 | 8 | 6 | 3 | 2 | 1 | | 34 |
| 35 | | 1 | 3 | 2 | 7 | 2 | 3 | | | | 18 |
| 40 | | | | | 2 | 1 | 2 | | | | 5 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | 1 | | | | | | 1 |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 2 | 46 | 102 | 132 | 123 | 40 | 42 | 11 | 3 | | |

NO. OF SAMPLES = 511
MEAN DIAMETER = 19.6 CM MAX = 53.3 CM MIN = 9.1 CM
MEAN LOG LENGTH = 8.8 M MAX = 17.1 M MIN = 2.4 M

N.T. LOG MEASUREMENT DATA
STAND TABLES BY SPECIES
GOVE >SINGLE TREES<    LOCALITY CODE 070    OLD STYLE DATA

01 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 6 | 12 | 4 | | | | | | | 22 |
| 20 | | 4 | 5 | 7 | | | | | | | 16 |
| 25 | | | 1 | | | | | | | | 1 |
| 30 | | | 2 | 1 | | | | | | | 3 |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 10 | 20 | 12 | | | | | | | |

NO. OF SAMPLES = 42
MEAN DIAMETER = 18.2 CM    MAX = 34.2 CM    MIN = 12.7 CM
MEAN LOG LENGTH = 5.9 M    MAX = 7.9 M    MIN = 3.7 M

02 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 2 | 10 | 5 | 5 | 1 | | | | | 23 |
| 20 | | 1 | 2 | 9 | 14 | 14 | 8 | 1 | | | 49 |
| 25 | | | 1 | 3 | 12 | 8 | 10 | 7 | 4 | | 45 |
| 30 | | | | | 5 | 6 | 7 | 2 | 2 | | 22 |
| 35 | | 1 | | | 4 | 2 | 3 | 2 | 4 | | 16 |
| 40 | | | | | | | | 1 | | | 1 |
| 45 | | | | | | | 1 | | | | 1 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 4 | 13 | 17 | 40 | 31 | 29 | 13 | 10 | | |

NO. OF SAMPLES = 157
MEAN DIAMETER = 23.9 CM    MAX = 45.2 CM    MIN = 13.0 CM
MEAN LOG LENGTH = 11.4 M    MAX = 18.0 M    MIN = 3.0 M

N.T. LOG MEASUREMENT DATA
STAND TABLES BY SPECIES
GOVE >SINGLE TREES<    LOCALITY CODE 070    OLD STYLE DATA

** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | 1 | | 1 |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | 1 | | |

NO. OF SAMPLES = 1
MEAN DIAMETER = 24.1 CM    MAX = 24.1 CM    MIN = 24.1 CM
MEAN LOG LENGTH = 17.1 M    MAX = 17.1 M    MIN = 17.1 M

**** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 8 | 22 | 9 | 5 | 1 | | | | | 45 |
| 20 | | 5 | 7 | 16 | 14 | 14 | 8 | 1 | | | 65 |
| 25 | | | 2 | 3 | 12 | 8 | 10 | 7 | 5 | | 47 |
| 30 | | | 2 | 1 | 5 | 6 | 7 | 2 | 2 | | 25 |
| 35 | | 1 | | | 4 | 2 | 3 | 2 | 4 | | 16 |
| 40 | | | | | | | | 1 | | | 1 |
| 45 | | | | | | | 1 | | | | 1 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 14 | 33 | 29 | 40 | 31 | 29 | 13 | 11 | | |

NO. OF SAMPLES = 200
MEAN DIAMETER = 22.7 CM    MAX = 45.2 CM    MIN = 12.7 CM
MEAN LOG LENGTH = 10.3 M    MAX = 18.0 M    MIN = 3.0 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

LAKE EVELLA LOCALITY CODE #11 NEW STYLE DATA

#1 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 5 | 7 | 1 | | | | | | | 13 |
| 20 | | | 5 | 11 | 1 | | | | | | 17 |
| 25 | | | | 3 | 11 | | | | | | 14 |
| 30 | | | | 2 | 6 | 2 | | | | | 10 |
| 35 | | | | | 5 | 2 | 2 | | | | 9 |
| 40 | | | | | 1 | | 1 | | | | 2 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 5 | 12 | 17 | 24 | 4 | 3 | | | | |

NO. OF SAMPLES = 65

MEAN DIAMETER = 24.5 CM MAX = 38.9 CM MIN = 14.0 CM

MEAN LOG LENGTH = 8.6 M MAX = 14.0 M MIN = 4.3 M

#2 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | 1 | 8 | 3 | 1 | | | | | 13 |
| 20 | | | | 7 | 10 | | | | | | 17 |
| 25 | | | 1 | 4 | 4 | 4 | 1 | 1 | | | 15 |
| 30 | | | | 1 | 9 | 6 | 2 | | 2 | | 20 |
| 35 | | 1 | | | 1 | 4 | 5 | 1 | 4 | | 16 |
| 40 | | | | | 1 | 1 | 2 | 5 | 2 | 4 | 15 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 1 | 2 | 20 | 28 | 16 | 10 | 7 | 8 | 4 | |

NO. OF SAMPLES = 96

MEAN DIAMETER = 27.7 CM MAX = 41.7 CM MIN = 15.2 CM

MEAN LOG LENGTH = 11.7 M MAX = 20.1 M MIN = 4.0 M

58 MELALEUCA SPP.

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 6 | 4 | 1 | 2 | | | | | | 13 |
| 20 | | 4 | 2 | 5 | 8 | | | | | | 19 |
| 25 | | 2 | 1 | 6 | 7 | | | | | | 16 |
| 30 | | 3 | 2 | 7 | 3 | 1 | | | | | 16 |
| 35 | | | 4 | 4 | 5 | 2 | 4 | 1 | | | 20 |
| 40 | | | 2 | 4 | 6 | 2 | 1 | 1 | 1 | | 17 |
| 45 | | | | 2 | 4 | | 1 | | | | 7 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 15 | 15 | 29 | 35 | 5 | 6 | 2 | 1 | | |

NO. OF SAMPLES = 108

MEAN DIAMETER = 29.9 CM MAX = 44.2 CM MIN = 14.0 CM

MEAN LOG LENGTH = 8.7 M MAX = 17.1 M MIN = 3.7 M

** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM MAX = .0 CM MIN = .0 CM

MEAN LOG LENGTH = .0 M MAX = .0 M MIN = .0 M

**** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 11 | 12 | 10 | 5 | 1 | | | | | 39 |
| 20 | | 4 | 7 | 23 | 19 | | | | | | 53 |
| 25 | | 2 | 2 | 13 | 22 | 4 | 1 | 1 | | | 45 |
| 30 | | 3 | 2 | 10 | 18 | 9 | 2 | | 2 | | 46 |
| 35 | | 1 | 4 | 4 | 11 | 8 | 11 | 2 | 4 | | 45 |
| 40 | | | 2 | 4 | 8 | 3 | 4 | 6 | 3 | 4 | 34 |
| 45 | | | | 2 | 4 | | 1 | | | | 7 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 21 | 29 | 66 | 87 | 25 | 19 | 9 | 9 | 4 | |

NO. OF SAMPLES = 269

MEAN DIAMETER = 27.5 CM MAX = 44.2 CM MIN = 14.0 CM

MEAN LOG LENGTH = 9.7 M MAX = 20.1 M MIN = 3.7 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

MELVILLE AND BATHURST ISLANDS, LOCALITY CODE 02 NEW STYLE DATA

### #1 EUCALYPTUS MINIATA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | 3 | | 2 | | | | | | 5 |
| 40 | | | 3 | 4 | 4 | | | | | | 11 |
| 45 | | | 3 | 6 | | 1 | | | | | 10 |
| 50 | | | 1 | 4 | 4 | 2 | | | | | 11 |
| 55 | | | 1 | 5 | 5 | 2 | | | | | 13 |
| >=57.5CM | | | 1 | 1 | 5 | | | | | | 7 |
| LENGTH CLASS TOTAL | | | 12 | 20 | 20 | 5 | | | | | |

NO. OF SAMPLES = 57

MEAN DIAMETER = 48.4 CM MAX = 61.5 CM MIN = 34.3 CM

MEAN LOG LENGTH = 8.5 M MAX = 12.8 M MIN = 5.5 M

### #2 EUCALYPTUS TETRODONTA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | 1 | 2 | 3 | | | | | | 6 |
| 40 | | 1 | 1 | 2 | 2 | 2 | | | 1 | | 9 |
| 45 | | | | 2 | 5 | 3 | 2 | | | | 12 |
| 50 | | | | 1 | 3 | 2 | 1 | 1 | | | 8 |
| 55 | | | | 3 | 3 | 1 | | 1 | | | 8 |
| >=57.5CM | | | | | | | 2 | | | | 2 |
| LENGTH CLASS TOTAL | | 1 | 2 | 10 | 16 | 8 | 5 | 2 | 1 | | |

NO. OF SAMPLES = 45

MEAN DIAMETER = 45.7 CM MAX = 60.7 CM MIN = 34.3 CM

MEAN LOG LENGTH = 10.4 M MAX = 17.1 M MIN = 4.9 M

### #3 EUCALYPTUS NESOPHILA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | 2 | 1 | 2 | | | | | | 5 |
| 40 | | 1 | 2 | 4 | 5 | | 1 | | | | 13 |
| 45 | | | 3 | 1 | 5 | 2 | | | | | 11 |
| 50 | | | | 4 | 1 | 3 | 1 | | | | 9 |
| 55 | | | | 2 | 6 | | | | | | 8 |
| >=57.5CM | | | 1 | 1 | 3 | 2 | 1 | | | | 8 |
| LENGTH CLASS TOTAL | | 1 | 8 | 13 | 22 | 7 | 3 | | | | |

NO. OF SAMPLES = 54

MEAN DIAMETER = 47.4 CM MAX = 61.7 CM MIN = 34.5 CM

MEAN LOG LENGTH = 9.4 M MAX = 14.0 M MIN = 4.9 M

### ** OTHER SPECIES **

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM MAX = .0 CM MIN = .0 CM

MEAN LOG LENGTH = .0 M MAX = .0 M MIN = .0 M

### **** ALL SPECIES ****

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | 6 | 3 | 7 | | | | | | 16 |
| 40 | | 2 | 6 | 10 | 11 | 2 | 1 | | 1 | | 33 |
| 45 | | | 6 | 9 | 10 | 6 | 2 | | | | 33 |
| 50 | | | 1 | 9 | 8 | 7 | 2 | 1 | | | 28 |
| 55 | | | 1 | 10 | 14 | 3 | | 1 | | | 29 |
| >=57.5CM | | | 2 | 2 | 8 | 2 | 3 | | | | 17 |
| LENGTH CLASS TOTAL | | 2 | 22 | 43 | 58 | 20 | 8 | 2 | 1 | | |

NO. OF SAMPLES = 156

MEAN DIAMETER = 47.3 CM MAX = 61.7 CM MIN = 34.3 CM

MEAN LOG LENGTH = 9.4 M MAX = 17.1 M MIN = 4.9 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

MELVILLE ISLAND WEST-GARDEN POINT,        LOCALITY CODE 0211        NEW STYLE DATA

01 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | 1 | | 3 | 3 | 1 | | | 8 |
| 25 | | | | | 1 | 4 | 5 | 2 | | | 12 |
| 30 | | | | | | 1 | 7 | 2 | 1 | | 11 |
| 35 | | | | | 1 | | 7 | 3 | 2 | | 13 |
| 40 | | | | | | | 5 | 2 | 3 | | 10 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | 1 | 2 | 8 | 27 | 10 | 6 | | |

NO. OF SAMPLES = 54

MEAN DIAMETER = 30.5 CM    MAX = 41.7 CM    MIN = 20.0 CM

MEAN LOG LENGTH = 14.2 M    MAX = 17.7 M    MIN = 7.3 M

02 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | 1 | 6 | 1 | | | | 8 |
| 25 | | 1 | | | 3 | 2 | 6 | 1 | | | 13 |
| 30 | | | | | 1 | 2 | 4 | 1 | 1 | | 9 |
| 35 | | 1 | | | | 2 | | 4 | 6 | 2 | 15 |
| 40 | | | | 1 | | | 2 | 3 | 3 | | 9 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 2 | | 1 | 5 | 12 | 13 | 9 | 10 | 2 | |

NO. OF SAMPLES = 54

MEAN DIAMETER = 30.4 CM    MAX = 41.1 CM    MIN = 19.6 CM

MEAN LOG LENGTH = 14.1 M    MAX = 20.7 M    MIN = 4.9 M

03 EUCALYPTUS NESOPHILA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | 2 | 5 | 3 | | | | | 10 |
| 25 | | | | | 2 | 4 | 5 | | | | 11 |
| 30 | | | | | 2 | 1 | 6 | 2 | | | 11 |
| 35 | | | | | | 2 | 5 | 3 | 2 | | 12 |
| 40 | | | | | | | 3 | 4 | 2 | 1 | 10 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | 2 | 9 | 10 | 19 | 9 | 4 | 1 | |

NO. OF SAMPLES = 54

MEAN DIAMETER = 30.4 CM    MAX = 41.7 CM    MIN = 19.6 CM

MEAN LOG LENGTH = 13.5 M    MAX = 20.7 M    MIN = 8.5 M

** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM    MAX = .0 CM    MIN = .0 CM

MEAN LOG LENGTH = .0 M    MAX = .0 M    MIN = .0 M

**** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | 3 | 6 | 12 | 4 | 1 | | | 26 |
| 25 | | 1 | | | 6 | 10 | 16 | 3 | | | 36 |
| 30 | | | | | 3 | 4 | 17 | 5 | 2 | | 31 |
| 35 | | 1 | | | 1 | 4 | 12 | 10 | 10 | 2 | 40 |
| 40 | | | | 1 | | | 10 | 9 | 8 | 1 | 29 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 2 | | 4 | 16 | 30 | 59 | 28 | 20 | 3 | |

NO. OF SAMPLES = 162

MEAN DIAMETER = 30.4 CM    MAX = 41.7 CM    MIN = 19.6 CM

MEAN LOG LENGTH = 13.9 M    MAX = 20.7 M    MIN = 4.9 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

MELVILLE ISLAND EAST. LOCALITY CODE 022 NEW STYLE DATA

## 01 EUCALYPTUS MINIATA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 1 | | | | | | | | | 1 |
| 15 | | 4 | 2 | 4 | | | | | | | 10 |
| 20 | | 1 | 1 | 3 | 2 | | | | | | 7 |
| 25 | | | | 1 | 5 | 2 | | | | | 8 |
| 30 | | | | | 5 | | 1 | | | | 6 |
| 35 | | | | 2 | 3 | 2 | 1 | 1 | | | 9 |
| 40 | | | | 1 | | | 1 | 1 | | | 3 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 6 | 3 | 11 | 15 | 4 | 3 | 2 | | | |

NO. OF SAMPLES = 44

MEAN DIAMETER = 25.2 CM MAX = 38.6 CM MIN = 12.2 CM

MEAN LOG LENGTH = 9.2 M MAX = 15.2 M MIN = 3.7 M

## 02 EUCALYPTUS TETRODONTA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | 1 | 1 | | | | | | | | | 2 |
| 15 | | | 5 | 1 | 1 | | | | | | 7 |
| 20 | | | 1 | 2 | 5 | | | | | | 8 |
| 25 | | | | 2 | 2 | 6 | | | | | 10 |
| 30 | | | | | 2 | 4 | 1 | 1 | | | 8 |
| 35 | | | 2 | | | 1 | 1 | 2 | | | 6 |
| 40 | | | | | | 2 | 1 | | | | 3 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 1 | 1 | 8 | 5 | 10 | 13 | 3 | 3 | | | |

NO. OF SAMPLES = 44

MEAN DIAMETER = 25.2 CM MAX = 39.1 CM MIN = 11.7 CM

MEAN LOG LENGTH = 10.0 M MAX = 15.8 M MIN = 2.4 M

## 03 EUCALYPTUS MESOPHILA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 4 | | | | | | | | | 4 |
| 15 | | 1 | 5 | | | | | | | | 6 |
| 20 | | | 3 | 4 | 1 | | | | | | 8 |
| 25 | | 1 | | 3 | 4 | | 1 | | | | 9 |
| 30 | | 1 | | 2 | | 2 | | | | | 5 |
| 35 | | | | 2 | 3 | 2 | 4 | | | | 11 |
| 40 | | | | | 1 | | | | | | 1 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 7 | 8 | 11 | 9 | 4 | 5 | | | | |

NO. OF SAMPLES = 44

MEAN DIAMETER = 25.1 CM MAX = 38.1 CM MIN = 11.7 CM

MEAN LOG LENGTH = 8.6 M MAX = 14.6 M MIN = 3.0 M

## 08 EUCALYPTUS BLEESERI

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | 6 | 2 | | | | | | | | 8 |
| 20 | | 1 | 5 | 2 | | | | | | | 8 |
| 25 | | 1 | 1 | 7 | | | | | | | 9 |
| 30 | | | 3 | 4 | 1 | 1 | | | | | 9 |
| 35 | | 1 | 2 | 2 | 1 | | | | | | 6 |
| 40 | | | 1 | 1 | 2 | | | | | | 4 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 9 | 14 | 16 | 4 | 1 | | | | | |

NO. OF SAMPLES = 44

MEAN DIAMETER = 25.3 CM MAX = 39.1 CM MIN = 12.7 CM

MEAN LOG LENGTH = 6.8 M MAX = 12.2 M MIN = 3.7 M

## ** OTHER SPECIES **

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM MAX = .0 CM MIN = .0 CM

MEAN LOG LENGTH = .0 M MAX = .0 M MIN = .0 M

## **** ALL SPECIES ****

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | 1 | 6 | | | | | | | | | 7 |
| 15 | | 11 | 14 | 5 | 1 | | | | | | 31 |
| 20 | | 2 | 10 | 11 | 8 | | | | | | 31 |
| 25 | | 2 | 1 | 13 | 11 | 8 | 1 | | | | 36 |
| 30 | | 1 | 3 | 6 | 8 | 7 | 2 | 1 | | | 28 |
| 35 | | 1 | 4 | 6 | 7 | 5 | 6 | 3 | | | 32 |
| 40 | | | 1 | 2 | 3 | 2 | 2 | 1 | | | 11 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 1 | 23 | 33 | 43 | 38 | 22 | 11 | 5 | | | |

NO. OF SAMPLES = 176

MEAN DIAMETER = 25.2 CM MAX = 39.1 CM MIN = 11.7 CM

MEAN LOG LENGTH = 8.7 M MAX = 15.8 M MIN = 2.4 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

MORGENELLA.  LOCALITY CODE P31  NEW STYLE DATA

### 01 EUCALYPTUS MINIATA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 3 | 4 | 4 | | | | | | | 11 |
| 15 | | 6 | 14 | 1 | | | | | | | 21 |
| 20 | | 2 | 8 | 9 | 5 | | | | | | 24 |
| 25 | | | 2 | 3 | 10 | 3 | | | | | 18 |
| 30 | | | 1 | 5 | 7 | 5 | 1 | 1 | | | 20 |
| 35 | | 1 | 3 | 3 | 8 | 5 | | | 1 | | 21 |
| 40 | | | | | 3 | 3 | | | | | 6 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 12 | 32 | 25 | 33 | 16 | 1 | 1 | 1 | | |

NO. OF SAMPLES = 121

MEAN DIAMETER = 24.3 CM  MAX = 41.9 CM  MIN = 9.1 CM

MEAN LOG LENGTH = 8.4 M  MAX = 17.1 M  MIN = 3.7 M

### 02 EUCALYPTUS TETRODONTA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 6 | 7 | 3 | | | | | | | 16 |
| 15 | | 2 | 4 | 7 | 4 | 2 | | | | | 19 |
| 20 | | 1 | 2 | 6 | 6 | 1 | 2 | | | | 18 |
| 25 | | | 2 | 3 | 3 | 3 | 3 | 1 | | | 15 |
| 30 | | | | 2 | 6 | 3 | 7 | 1 | | | 19 |
| 35 | | | | 3 | 5 | 3 | 1 | 2 | 3 | | 17 |
| 40 | | | | 1 | | 2 | 1 | | 2 | 1 | 7 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 9 | 15 | 25 | 24 | 14 | 14 | 4 | 5 | 1 | |

NO. OF SAMPLES = 111

MEAN DIAMETER = 23.7 CM  MAX = 41.1 CM  MIN = 9.4 CM

MEAN LOG LENGTH = 10.0 M  MAX = 21.3 M  MIN = 3.7 M

### 03 EUCALYPTUS NESOPHILA

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | 10 | 4 | | | | | | | | 14 |
| 15 | | 4 | 7 | 7 | | | | | | | 18 |
| 20 | | 1 | 10 | 9 | 1 | | | | | | 21 |
| 25 | | | 1 | 10 | 8 | 2 | | | | | 21 |
| 30 | | | 2 | 3 | 16 | 1 | | | | | 22 |
| 35 | | | | 5 | 4 | 3 | 2 | 1 | | | 15 |
| 40 | | | 1 | 1 | 4 | 3 | 5 | 1 | | | 15 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 15 | 25 | 35 | 33 | 9 | 7 | 2 | | | |

NO. OF SAMPLES = 126

MEAN DIAMETER = 24.8 CM  MAX = 41.4 CM  MIN = 9.1 CM

MEAN LOG LENGTH = 8.4 M  MAX = 15.2 M  MIN = 3.0 M

### 60 MELALEUCA SPP.

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | 1 | 4 | 5 | 3 | 1 | | | | | | 14 |
| 15 | | 1 | 3 | 3 | 8 | | | | | | 15 |
| 20 | | | 3 | 8 | 8 | 3 | | | | | 22 |
| 25 | | 1 | 1 | 4 | 8 | 8 | 4 | | | | 26 |
| 30 | | | 1 | | 4 | 3 | 5 | 1 | 1 | | 15 |
| 35 | | | | 1 | 6 | 7 | 5 | 2 | 1 | 1 | 23 |
| 40 | | | | | 2 | 4 | 3 | 3 | 3 | 1 | 16 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 1 | 6 | 13 | 19 | 37 | 25 | 17 | 6 | 5 | 2 | |

NO. OF SAMPLES = 131

MEAN DIAMETER = 25.5 CM  MAX = 41.7 CM  MIN = 8.9 CM

MEAN LOG LENGTH = 10.7 M  MAX = 20.7 M  MIN = 2.4 M

### ** OTHER SPECIES **

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM  MAX = .0 CM  MIN = .0 CM

MEAN LOG LENGTH = .0 M  MAX = .0 M  MIN = .0 M

### **** ALL SPECIES ****

MERCHANTABLE LOG LENGTH (IN 2M CLASSES)

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| <12.5CM | 1 | 23 | 20 | 10 | 1 | | | | | | 55 |
| 15 | | 13 | 28 | 18 | 12 | 2 | | | | | 73 |
| 20 | | 4 | 23 | 32 | 20 | 4 | 2 | | | | 85 |
| 25 | | 1 | 6 | 20 | 29 | 16 | 7 | 1 | | | 80 |
| 30 | | | 4 | 10 | 33 | 12 | 13 | 3 | 1 | | 76 |
| 35 | | 1 | 3 | 12 | 23 | 18 | 8 | 5 | 5 | 1 | 76 |
| 40 | | | 1 | 2 | 9 | 12 | 9 | 4 | 5 | 2 | 44 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 1 | 42 | 85 | 104 | 127 | 64 | 39 | 13 | 11 | 3 | |

NO. OF SAMPLES = 489

MEAN DIAMETER = 24.6 CM  MAX = 41.9 CM  MIN = 8.9 CM

MEAN LOG LENGTH = 9.4 M  MAX = 21.3 M  MIN = 2.4 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

ROVE. LOCALITY CODE #7 NEW STYLE DATA

#1 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | |
| <12.5CM | | 1 | 1 | | | | | | | | 2 |
| 15 | | 9 | 19 | 7 | | | | | | | 35 |
| 20 | | 3 | 3 | 15 | 1 | | | | | | 22 |
| 25 | | 1 | 4 | 2 | | | | | | | 7 |
| 30 | | | | 2 | 1 | | | | | | 3 |
| 35 | | 1 | | 7 | 1 | | | | | | 9 |
| 40 | | 1 | | 1 | | | | | | | 2 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 16 | 27 | 34 | 3 | | | | | | |

NO. OF SAMPLES = 80

MEAN DIAMETER = 20.5 CM MAX = 38.9 CM MIN = 9.4 CM

MEAN LOG LENGTH = 8.0 M MAX = 10.1 M MIN = 3.0 M

#2 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | |
| <12.5CM | | 5 | 4 | 5 | | | | | | | 14 |
| 15 | 1 | 4 | 7 | 5 | 8 | | | | | | 25 |
| 20 | 1 | 7 | 8 | 3 | 10 | 5 | 4 | | | | 38 |
| 25 | | 3 | 4 | 6 | 4 | 5 | 5 | 1 | 1 | | 29 |
| 30 | | | 3 | 7 | 6 | 4 | 7 | 2 | 1 | | 30 |
| 35 | | 3 | 6 | 4 | 4 | 3 | 4 | | 1 | | 25 |
| 40 | | | | 1 | 2 | 2 | 1 | | | | 6 |
| 45 | | 1 | | | | | | | | | 1 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 2 | 23 | 32 | 31 | 34 | 19 | 21 | 3 | 3 | | |

NO. OF SAMPLES = 168

MEAN DIAMETER = 24.1 CM MAX = 44.2 CM MIN = 8.0 CM

MEAN LOG LENGTH = 9.0 M MAX = 18.3 M MIN = 2.4 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

ROVE. LOCALITY CODE #7 NEW STYLE DATA

** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | |
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM MAX = .0 CM MIN = .0 CM

MEAN LOG LENGTH = .0 M MAX = .0 M MIN = .0 M

**** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | |
| <12.5CM | | 6 | 5 | 5 | | | | | | | 16 |
| 15 | 1 | 13 | 26 | 12 | 8 | | | | | | 60 |
| 20 | 1 | 10 | 11 | 18 | 11 | 5 | 4 | | | | 60 |
| 25 | | 4 | 8 | 8 | 4 | 5 | 5 | 1 | 1 | | 36 |
| 30 | | | 3 | 9 | 7 | 4 | 7 | 2 | 1 | | 33 |
| 35 | | 4 | 6 | 11 | 5 | 3 | 4 | | 1 | | 34 |
| 40 | | 1 | | 2 | 2 | 2 | 1 | | | | 8 |
| 45 | | 1 | | | | | | | | | 1 |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 2 | 39 | 59 | 65 | 37 | 19 | 21 | 3 | 3 | | |

NO. OF SAMPLES = 248

MEAN DIAMETER = 22.9 CM MAX = 44.9 CM MIN = 8.0 CM

MEAN LOG LENGTH = 8.2 M MAX = 18.3 M MIN = 2.4 M

N.T. LOG MEASUREMENT DATA

STAND TABLES BY SPECIES

MANINGRIDA LOCALITY CODE 001 NEW STYLE DATA

### 01 EUCALYPTUS MINIATA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | |
| <12.5CM | | 3 | 10 | 4 | 1 | | | | | | 18 |
| 15 | | 2 | 8 | 11 | 3 | | | | | | 24 |
| 20 | | | 3 | 13 | 11 | 1 | | | | | 28 |
| 25 | | 1 | 1 | 4 | 10 | 3 | | | | | 19 |
| 30 | | | 3 | 7 | 9 | 3 | 1 | | | | 23 |
| 35 | | | 1 | 5 | 11 | 3 | 4 | | | | 24 |
| 40 | | | 2 | 2 | 10 | 3 | 4 | | | | 21 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 6 | 28 | 46 | 55 | 13 | 9 | | | | |

NO. OF SAMPLES = 157

MEAN DIAMETER = 25.4 CM MAX = 41.7 CM MIN = 8.9 CM

MEAN LOG LENGTH = 9.0 M MAX = 14.6 M MIN = 4.0 M

### 02 EUCALYPTUS TETRODONTA

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | |
| <12.5CM | | | 7 | 8 | 4 | | | | | | 19 |
| 15 | | | 3 | 4 | 10 | 2 | | | | | 19 |
| 20 | | | 1 | 4 | 13 | 3 | 4 | 1 | | | 26 |
| 25 | | | 1 | 5 | 9 | 5 | 5 | 1 | 1 | | 27 |
| 30 | | | | 2 | 9 | 4 | 3 | 4 | | | 22 |
| 35 | | | | 3 | 2 | 7 | 7 | 4 | 1 | | 24 |
| 40 | | | | 3 | 2 | 4 | 2 | 6 | 2 | | 19 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | 12 | 29 | 49 | 25 | 21 | 16 | 4 | | |

NO. OF SAMPLES = 156

MEAN DIAMETER = 25.3 CM MAX = 41.7 CM MIN = 9.0 CM

MEAN LOG LENGTH = 11.0 M MAX = 18.9 M MIN = 5.2 M

### 06 EUCALYPTUS BLEESERI

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | |
| <12.5CM | | 13 | 4 | 2 | | | | | | | 19 |
| 15 | | 3 | 11 | 5 | 2 | | | | | | 21 |
| 20 | | 2 | 8 | 11 | 4 | 1 | | | | | 26 |
| 25 | | 1 | 9 | 6 | 5 | | | | | | 21 |
| 30 | | 1 | 5 | 7 | 11 | 1 | | | | | 25 |
| 35 | | 2 | 5 | 6 | 6 | 3 | 1 | | | | 23 |
| 40 | | 3 | 2 | 4 | 8 | 2 | 2 | | | | 21 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | 25 | 44 | 41 | 36 | 7 | 3 | | | | |

NO. OF SAMPLES = 156

MEAN DIAMETER = 25.3 CM MAX = 41.7 CM MIN = 8.9 CM

MEAN LOG LENGTH = 7.6 M MAX = 14.0 M MIN = 3.7 M

### 08 MELALEUCA SPP.

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | |
| <12.5CM | 6 | 11 | | | | | | | | | 17 |
| 15 | | 8 | 10 | 5 | 1 | | | | | | 24 |
| 20 | | 2 | 9 | 10 | 1 | 1 | | | | | 23 |
| 25 | | 1 | 5 | 7 | 7 | 1 | | | | | 21 |
| 30 | | 4 | 4 | 7 | 9 | 2 | | | | | 26 |
| 35 | | 3 | 7 | 4 | 10 | | 1 | | | | 25 |
| 40 | | | 1 | 4 | 10 | 2 | | | | | 17 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 6 | 29 | 36 | 37 | 38 | 6 | 1 | | | | |

NO. OF SAMPLES = 153

MEAN DIAMETER = 25.3 CM MAX = 41.7 CM MIN = 8.9 CM

MEAN LOG LENGTH = 7.2 M MAX = 13.4 M MIN = 2.4 M

### ** OTHER SPECIES **

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | |
| <12.5CM | | | | | | | | | | | |
| 15 | | | | | | | | | | | |
| 20 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 30 | | | | | | | | | | | |
| 35 | | | | | | | | | | | |
| 40 | | | | | | | | | | | |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | | | | | | | | | | | |

NO. OF SAMPLES = 0

MEAN DIAMETER = .0 CM MAX = .0 CM MIN = .0 CM

MEAN LOG LENGTH = .0 M MAX = .0 M MIN = .0 M

### **** ALL SPECIES ****

| DBHOB (IN 5CM CLASSES) | MERCHANTABLE LOG LENGTH (IN 2M CLASSES) | | | | | | | | | | DIAM CLASS TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3M | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | >=19M | |
| <12.5CM | 6 | 27 | 21 | 14 | 5 | | | | | | 73 |
| 15 | | 13 | 32 | 25 | 16 | 2 | | | | | 88 |
| 20 | | 4 | 21 | 38 | 29 | 6 | 4 | 1 | | | 103 |
| 25 | | 3 | 16 | 22 | 31 | 9 | 5 | 1 | 1 | | 88 |
| 30 | | 5 | 12 | 23 | 38 | 10 | 4 | 4 | | | 96 |
| 35 | | 5 | 13 | 18 | 29 | 13 | 13 | 4 | 1 | | 96 |
| 40 | | 3 | 5 | 13 | 30 | 11 | 8 | 6 | 2 | | 78 |
| 45 | | | | | | | | | | | |
| 50 | | | | | | | | | | | |
| 55 | | | | | | | | | | | |
| >=57.5CM | | | | | | | | | | | |
| LENGTH CLASS TOTAL | 6 | 60 | 120 | 153 | 178 | 51 | 34 | 16 | 4 | | |

NO. OF SAMPLES = 622

MEAN DIAMETER = 25.3 CM MAX = 41.7 CM MIN = 8.9 CM

MEAN LOG LENGTH = 8.7 M MAX = 18.9 M MIN = 2.4 M

# APPENDIX 3

## COEFFICIENTS OF FINAL MODELS

All models are of the form: $V = b_0 + b_1 D^{b_2} H^{b_3}$

| Locality | Species | No. Obs. | $b_0$ | $b_1$ | $b_2$ | $b_3$ |
|---|---|---|---|---|---|---|
| Old style data | | | | | | |
| 02 | 01 | 150 | -.06997 | .000262421 | 1.7286 | .69607 |
| 03 | 01 | 95 | -.00454 | .000069368 | 1.9987 | .79316 |
| 07 | 01 | 86 | -.00446 | .000050560 | 2.0401 | .86794 |
| 02+03+07 | 02 | 631 | -.00734 | .000061205 | 2.1025 | .70117 |
| 02+03 | 03 | 160 | -.05387 | .000094267 | 2.0200 | .65010 |
| New style data | | | | | | |
| 011 | 01 | 65 | -.02780 | .000416630 | 1.6506 | .57679 |
| 02+022 | 01 | 101 | +.01766 | .000027042 | 2.2968 | .76166 |
| 0211 | 01 | 54 | -.05948 | .000485412 | 1.6985 | .53134 |
| 031 | 01 | 121 | -.00414 | .000095883 | 1.9697 | .70348 |
| 07 | 01 | 80 | -.01023 | .000026946 | 2.2507 | .84351 |
| 091 | 01 | 157 | -.00227 | .000049904 | 2.1971 | .65424 |
| 011 | 02 | 96 | -.02090 | .000171405 | 1.8557 | .70849 |
| 02+0211+022 | 02 | 143 | -.00240 | .000061952 | 2.1585 | .65853 |
| 031 | 02 | 111 | -.00158 | .000059867 | 2.1984 | .59790 |
| 07 | 02 | 168 | -.01052 | .000145252 | 1.8472 | .73099 |
| 091 | 02 | 156 | -.00961 | .000077066 | 2.1225 | .61433 |
| 02+022 | 03 | 98 | +.00379 | .000033851 | 2.2329 | .79919 |
| 0211 | 03 | 54 | +.01818 | .000049448 | 2.3366 | .48914 |
| 031 | 03 | 126 | -.00402 | .000047002 | 2.3029 | .55522 |
| 022 | 06 | 44 | -.01594 | .000275422 | 1.8279 | .47320 |
| 091 | 06 | 156 | +.00067 | .000084702 | 2.0781 | .64573 |
| 011 | 68 | 108 | +.00902 | .000099713 | 1.8119 | .93829 |
| 031 | 68 | 131 | -.00366 | .000084725 | 2.0364 | .61603 |
| 091 | 68 | 153 | -.00137 | .000093819 | 1.9440 | .72565 |
| Old style data Species of minor occurrence | | | | | | |
| 02 | 06 | 21 | +.07249 | .0000003780 | 3.7209 | 1.5997 |
| 02+03+07 | other | 56 | -.00583 | .000046796 | 2.0778 | .82753 |